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SUBSONIC RELATIONSHIPS BETWEEN PRESSURE ALTITUDE, CALIBRATED AIRSPEED, AND MACH NUMBER

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SEPTEMBER 2012

TECHNICAL INFORMATION HANDBOOK

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EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
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14. ABSTRACT

This handbook derives equations for pressure altitude, calibrated airspeed, and Mach number valid for subsonic Mach numbers in the troposphere and the stratosphere using the 1976 U.S. standard atmosphere.

Equations are also developed for equivalent airspeed, true airspeed, local speed of sound, and incompressible dynamic pressure. Numerical examples are presented solving for pressure altitude, calibrated airspeed, or Mach number using the other two parameters.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

The purpose of this handbook is twofold:

1. Present the subsonic relationships among pressure altitude, calibrated airspeed, and Mach number, and

2. Show that the relationships between calibrated airspeed and Mach number at a given pressure altitude are independent of the ambient air temperature or the total air temperature.

Equations relating ambient air pressure and pressure altitude were derived for the 1976 U.S. standard atmosphere. The equation for Mach number as a function of the ratio of total air pressure to ambient air pressure comes from classical gas dynamics. The equation for the speed of sound as a function of ambient air temperature and the sea level, standard day value were obtained from the 1976 U.S. standard atmosphere. The equation for true airspeed was based on the definition of Mach number, true airspeed divided by the local speed of sound. The equations for equivalent airspeed and for calibrated airspeed were developed from the true airspeed equation by setting selected local parameter values to their sea level, standard day equivalents.

Numerical examples are presented solving for pressure altitude, calibrated airspeed, or Mach number using the other two parameters.

Understanding and using these relationships properly is important to every flight tester who provides flight test conditions in their reports. This document will promote a proper understanding and use of these relationships.

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TABLE OF CONTENTS

Page No.

BACKGROUND

The purpose of this handbook is twofold:

1. Present the subsonic relationships among pressure altitude, calibrated airspeed, and Mach number, and

2. Show that the relationships between calibrated airspeed and Mach number at a given pressure altitude are independent of the ambient air temperature or the total air temperature.

The atmospheric model used in the handbook is the *U.S. Standard Atmosphere*, 1976, reference 1. The 1976 U.S. standard atmosphere ambient air pressure, pressure altitude, geopotential height, and ambient air temperature relationships are identical to those of the *Committee on Extension to the Standard Atmosphere: U.S. Standard Atmosphere*, 1962, reference 2, below 50 kilometers, 164,042 feet. The two atmospheric models, the 1962 and the 1976 U.S. standard atmospheres, use different gravity models. Therefore, the relationships between geometric heights (tapeline heights) and geopotential heights are different.

The 1964 International Civil Aviation Organization (ICAO) standard atmosphere is identical to the 1976 U.S. standard atmosphere up to 32 kilometers, 104,987 feet. The 1993 ICAO standard atmosphere, *Manual of the ICAO International Standard Atmosphere (Extended to 80 Kilometers [262,500 Feet])*, reference 3, is identical to the 1976 U.S. standard atmosphere from -1,000 meters (-3,281 feet) through 80,000 meters (262,467 feet) geopotential height.

This handbook, except for appendix B, was developed for the two lowest segments of the atmosphere (below 20,000 meters or 65,000 feet) and for subsonic Mach numbers. Some supersonic relationships are derived in appendix B.

This handbook was developed assuming that these relationships would be used with a test aircraft that had sensitive pressure sensors used to record static and total air pressures and that the aircraft position error corrections for the static pressure measurements were known. Relationships were developed independent of ambient or total air temperatures for pressure altitude, calibrated airspeed, and Mach number for subsonic Mach numbers.

USE OF THIS HANDBOOK

This handbook provides three methods of determining calibrated airspeed or Mach number or pressure altitude given the other two variables:

1. Plots in appendix F provide the quickest but least accurate answer.

2. Tables in appendix G provide a more accurate answer for subsonic Mach numbers.

3. Equations in the main body provide for the most accurate answer for subsonic Mach numbers.

RESOLUTION AND SIGNIFICANT FIGURES

Many of the constants in this handbook have internationally accepted values or are the products or quotients of accepted values. The number of significant figures for a constant should not be interpreted to represent the accuracy to which the constant can typically be measured. In general, in flight test, the following uncertainties are achievable in the troposphere: Pressure altitude, 10 to 20 feet; static air pressure, 0.001 to 0.003 inches of mercury; calibrated airspeed, 0.1 to 0.2 knot; and Mach number, 0.0005.

The constants in the equations relating ambient air pressures and pressure altitudes require up to eight significant figures to duplicate the values in the tables in references 1, 2, and 3. See appendix D for numerical examples of the importance of the number of significant figures.

LIMITATIONS OF VALIDITY

The scope of this handbook is limited in two aspects:

1. Only the two lowest segments of the atmosphere, the troposphere and the stratosphere, are addressed. This covers the altitude range from sea level through 20,000 geopotential meters, approximately 65,000 geopotential feet.

2. The main body of the handbook only addresses subsonic Mach numbers. Supersonic Mach numbers are considered in appendices B and F. The equations were derived assuming that the ratio of specific heats, γ or gamma, was a constant and was exactly equal to 1.400. The theoretical value of the ratio of specific heats for an ideal diatomic gas is 1.4, reference 4.

An AFFTC office memo, reference 5, made the following statements referring to the assumptions that $\gamma = 1.4$ and that air could be assumed to act as a perfect gas, $P = \rho RT$:

> "…, as the flight Mach number increases beyond 2 the total temperature reaches values at which these assumptions are no longer valid. At approximately 400 deg K (720 deg F) the value of the specific heat ratio begins to fall significantly below 1.4…"

NACA Research Memorandum number L7K26, reference 6, makes the following statements:

> "The assumption that air is a perfect gas with a value of γ of 1.400 is valid for the conditions usually encountered in the subsonic and lower supersonic speed regions for normal stagnation conditions. For Mach numbers greater than about 4.0, however, or for unusual stagnation conditions the behavior of air will depart appreciably from that of a perfect gas if the liquefaction condition is approached, and caution should be used in applying the results in the tables at the higher Mach numbers."

Thus, somewhere between a Mach number of 2 and 4, the equations derived assuming a ratio of specific heats of 1.4 are no longer valid.[1]

The values for the ratios of specific heats as a function of air temperature have been modeled in different ways in the technical references, references 6 through 12. However, all have similar trends: The ratio of specific heats is greater than 1.4 at low temperatures and decrease to less than 1.3 at very high temperatures. Table 1, extracted from table C.4 on pages 700 through 704 in reference 10, is provided to illustrate the range of the ratio of specific heats.

[1] The AFFTC has assumed that the equations have been valid for all non-hypersonic aircraft except for the XB-70 and the A-11/A-12/YF-12/SR-71 aircraft. Those aircraft were all capable of cruising at Mach 3 or faster.

Table 1 Ratio of Specific Heats for Air*

Temperature (K)	Ratio of specific heats, γ (n/d)
50	1.3854
100	1.3920
150	1.3967
200	1.3995
250	1.4006
300	1.4000
350	1.3982
400	1.3951
450	1.3912
500	1.3865
550	1.3814
600	1.3759
700	1.3646
800	1.3538
900	1.3441
1,000	1.3361

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

*Extracted from Gas Dynamics by Maurice J. Zucrow and Joe D. Hoffman, table C.4 on pages 700 through 704, reference 10.

DERIVATION OF AN ATMOSPHERIC MODEL

Other atmospheric model derivations may be found in many college textbooks for aircraft design or aircraft performance. They all follow the same basic steps and they all make similar assumptions. This derivation is included here for completeness.

The derivation starts with an element of dry air in static equilibrium, figure 1.

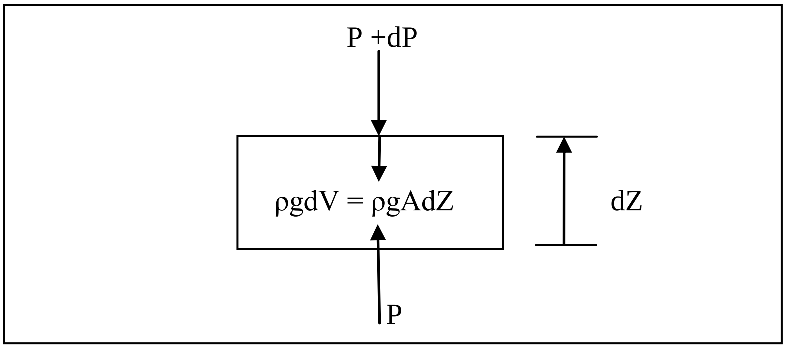

Figure 1 Freebody Diagram of an Element of Air

For the element of air to be in equilibrium, the summation of the vertical forces must be zero. They must balance, equation 1.

$$\Sigma F = 0 = PA - (P + dP)A - \rho g A dZ \qquad (1)$$

Where:

P	=	pressure acting upward on the lower surface of the element
$(P + dP)$	=	pressure acting downward on the upper surface of the element
$\rho gAdZ$	=	the weight of the air inside the element
A	=	surface area of the top or the bottom of the element
ρ	=	air density within the element
g	=	local acceleration due to gravity

Dividing equation 1 by the area, A, and canceling like terms, PA, simplifies equation 1 to equation 2.

$$dP = -\rho g dZ \qquad (2)$$

A relationship between ambient air pressure and altitude can be created by integrating equation 2 over a range of heights, Z_0 to Z_1, equation 3.

$$\int_0^1 dP = P_1 - P_0 = -\int_0^1 \rho g dZ \qquad (3)$$

Relationships for air density and for the local acceleration due to gravity must be developed before the integral can be solved.

RELATIONSHIP FOR AIR DENSITY

A relationship for air density can be developed by introducing the perfect gas equation of state, equation 4:

$$P = \rho RT \tag{4}$$

$$\rho = \frac{P}{RT} \tag{5}$$

Where:

P	=	ambient air pressure
ρ	=	air density
R	=	gas constant for dry air
T	=	ambient air temperature in absolute units (degrees R or K)

<u>Non-dimensional Equation of State:</u>

The equation of state is non-dimensionalized by introducing three non-dimensional parameters: The ambient air pressure ratio, δ, the ambient air density ratio, σ, and the ambient air temperature ratio, θ, equations 4 through 9.

$$P = \rho RT \tag{4}$$

For the special case of sea level, standard day:

$$P_{SL} = \rho_{SL} RT_{SL} \tag{6}$$

Dividing equation 4 by equation 6 produces equations 7, 8, and 9.

$$\frac{P}{P_{SL}} = \frac{\rho}{\rho_{SL}}\left(\frac{R}{R}\right)\frac{T}{T_{SL}} \tag{7}$$

$$\frac{P}{P_{SL}} = \left(\frac{\rho}{\rho_{SL}}\right)\left(\frac{T}{T_{SL}}\right) \tag{8}$$

$$\delta = \sigma\theta \tag{9}$$

Where:

SL = sea level, standard day

These non-dimensional parameters will be used later in this handbook.

Specific Gas Constant for Dry Air:

This handbook, except in appendix C, assumes a value of 287.052 87 [$(m/sec)^2/K$] for the specific gas constant for dry air. This is the value documented in table A on page E-viii and in table C on page xi of reference 3. Additional information concerning the gas constant can be found in appendix C.

RELATIONSHIP FOR THE LOCAL ACCELERATION DUE TO GRAVITY

A relationship for the local acceleration due to gravity as a function of geometric height above mean sea level normally used for atmospheric models is the inverse square gravity model, equation 10. Both the 1976 U.S. standard atmosphere and the 1993 ICAO international standard atmosphere models assume a spherical, homogeneous Earth.

$$g = g_o \left[\frac{r_o}{(r_o+Z)} \right]^2 \tag{10}$$

Where:

g = local acceleration due to gravity

g_o = reference acceleration due to gravity at mean sea level

r_o = reference radius of the Earth

Z = local geometric height above mean sea level

The reference values used by both the 1976 U.S. standard atmosphere and by the 1993 ICAO international standard atmosphere are summarized in table 2.

Table 2 Reference Values for the Acceleration due to Gravity at Sea Level and for the Radius of the Earth for the 1976 U.S. Standard Atmosphere

Parameter	Symbol	Units	Value
Acceleration due to gravity	g_o	$m/(sec)^2$	9.80665 (exact)
		$ft/(sec)^2$	32.174 049
Radius of the Earth	r_o	km	6356.766
		ft	20,855,532

Notes: 1. "exact" refers to a value accepted by international agreement as an exact value.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

Introducing Geopotential Height:

The geopotential height 'H' is introduced, equation 11, to avoid the necessity of integrating the relationship for the local acceleration due to gravity in equation 3.

$$g\,dZ = g_o\,dH \tag{11}$$

$$\int g\,dZ = \int g_0\,dH = g_0 \int dH \tag{12}$$

Where:

g = local acceleration due to gravity

dZ = incremental change in geometric height

g_o = reference acceleration due to gravity, a constant

dH = incremental change in geopotential height

An incremental change in the measured geometric or tapeline height, a foot or a meter for example, is independent of gravitational variations. An incremental change in geopotential height varies in length with changes in the magnitude of the local acceleration due to gravity.

Raising a mass above a horizontal reference plane will increase its potential energy. For example, raising a kilogram mass 1 meter vertically in a gravity field equal to 9.80665 (m/sec^2) would increase its potential energy by equation 13.

$$\Delta PE = mg\Delta Z \tag{13}$$

Where:

ΔPE = an incremental change in potential energy

m = mass

g = local acceleration due to gravity

ΔZ = incremental change in geometric height

Note: For this example, it is assumed that the value for the local acceleration due to gravity does not change over the small change in height.

$$\Delta PE = [1\ (\text{kg})][9.80665\ (\text{m/sec}^2)][1\ (\text{m})]$$

$$= 9.80665\ [\text{kg} \cdot (\text{m/sec}^2)] \cdot \text{m}$$

$$= 9.80665\ (\text{N} \cdot \text{m})$$

The letter 'N' represents a newton named in honor of Sir Isaac Newton, the British scientist. One newton of force is equal to 1 kilogram meter per second squared. A newton is a unit of force while a newton per square meter is a unit of pressure. A newton per square meter is also known as a 'pascal.'

If the same 1 kilogram mass were raised in a gravity field less than 9.80665 (m/sec^2) to achieve the same increase in potential energy, it would need to be raised a larger increment in geometric height. A geopotential meter is simply that incremental height. For a given physical distance, its length in geopotential feet or meters is always less than its length in geometric feet or meters if the local acceleration due to gravity is less than the reference value.

The physical length of a geopotential foot or meter increases in actual length with increasing distance above the Earth's surface because of the decreasing local acceleration due to gravity.

Examples of the differences between geometric and geopotential heights may be found in tables 3 and 4. Note that the model-predicted accelerations are within 0.5 percent of the reference sea level value until above 50,000 feet of geometric height, table 4.

Table 3 Comparison of Geometric and Geopotential Heights for the 1976 U.S. Standard Atmosphere

Geometric Height (ft)	Geopotential Height (ft)	Difference (ft)	Acceleration Due to Gravity (ft/sec^2)
0	0	0	32.174
10,000	9,995	5	32.142
20,000	19,981	19	32.113
30,000	29,957	43	32.081
40,000	39,923	77	32.052
50,000	49,880	120	32.020
60,000	59,828	172	31.991
70,000	69,766	234	31.958
80,000	79,694	306	31.929
90,000	89,613	387	31.897
100,000	99,523	477	31.868
110,000	109,423	577	31.836
120,000	119,313	687	31.807
130,000	129,195	805	31.775
140,000	139,066	934	31.746
150,000	148,929	1,071	31.717

Notes: 1. The 1976 U.S. standard atmosphere and the 1993 ICAO international standard atmosphere gravity models are identical.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

Table 4 Comparison of Geometric and Geopotential Heights for the
1976 U.S. Standard Atmosphere Model

Geopotential Height (ft)	Geometric Height (ft)	Difference (ft)	Gravity Ratio (n/d)
0	0	0	1.0000
5,000	5,001	1	0.9995
10,000	10,005	5	0.9990
15,000	15,011	11	0.9986
20,000	20,019	19	0.9981
25,000	25,030	30	0.9976
30,000	30,043	43	0.9971
35,000	35,059	59	0.9966
40,000	40,077	77	0.9962
45,000	45,097	97	0.9957
50,000	50,120	120	0.9952
55,000	55,145	145	0.9947
60,000	60,173	173	0.9943
65,000	65,203	203	0.9938
70,000	70,236	236	0.9933

Notes:
1. These data were extracted from pages 152 - 164, table V, U.S. Standard Atmosphere, 1976, reference 1.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

<u>Introducing Pressure Altitude:</u>

Pressure altitude is defined as the geopotential height at which an ambient air pressure exists in the standard day atmospheric model. Think of pressure altitude as a point in the atmosphere at which a pressure exists, not as a height above sea level. The relationship between ambient air pressure and pressure altitude is defined by an atmospheric model, such as the 1976 U.S. standard atmosphere or the 1993 ICAO international standard atmosphere, references 1 and 3. Except on a standard day from the surface to the point of interest in the atmosphere (a condition which has probably never existed), there is no direct connection between pressure altitude and height above sea level or height above the ground.

MODIFYING THE INTEGRAL

Now that we have relationships for air density and for the local acceleration due to gravity, we can solve equation 3 if we know the variation of the ambient air temperature with changes in geopotential height. Substituting equation 5 for air density and equation 12 for the local acceleration due to gravity prepares the integral, equation 3, for generating a solution, equation 17.

$$\int dP = -\int \rho g dZ \tag{3}$$

$$dP = -\rho g dZ$$

$$\rho = \frac{P}{RT} \tag{5}$$

Substituting equation 5 into equation 3 produces equation 14.

$$dP = -\left(\frac{P}{RT}\right) gdZ$$

$$\frac{dP}{P} = -\left(\frac{1}{RT}\right) gdZ$$

$$\int \left(\frac{1}{P}\right) dP = -\int \left(\frac{1}{RT}\right) gdZ \tag{14}$$

Now we will switch from geometric altitudes to geopotential altitudes using equation 12.

$$\int gdZ = \int g_0 dH \tag{12}$$

Substituting equation 12 into the right side of equation 14 produces equation 15.

$$\int \left(\frac{1}{P}\right) dP = -\int \left(\frac{1}{RT}\right) g_0 dH \tag{15}$$

Recognizing that the gas constant, R, and the reference acceleration due to gravity, g_0, are constants; they are pulled out of the integral on the right side of equation 15.

$$\int \left(\frac{dP}{P}\right) = -\left(\frac{g_0}{R}\right) \int \left(\frac{1}{T}\right) dH \tag{16}$$

$$\int \left(\frac{dP}{P}\right) = -g_0 \left(\frac{1}{R}\right) \int \left(\frac{1}{T}\right) dH \tag{17}$$

This equation, equation 17, can now be easily integrated either for a constant ambient air temperature or for one linearly varying with geopotential height. All of the U.S. standard atmospheres and the 1993 ICAO international standard atmosphere model the segments of the modeled atmosphere with one of these two temperature variation types. Figure 2 depicts a standard day ambient air temperature profile.

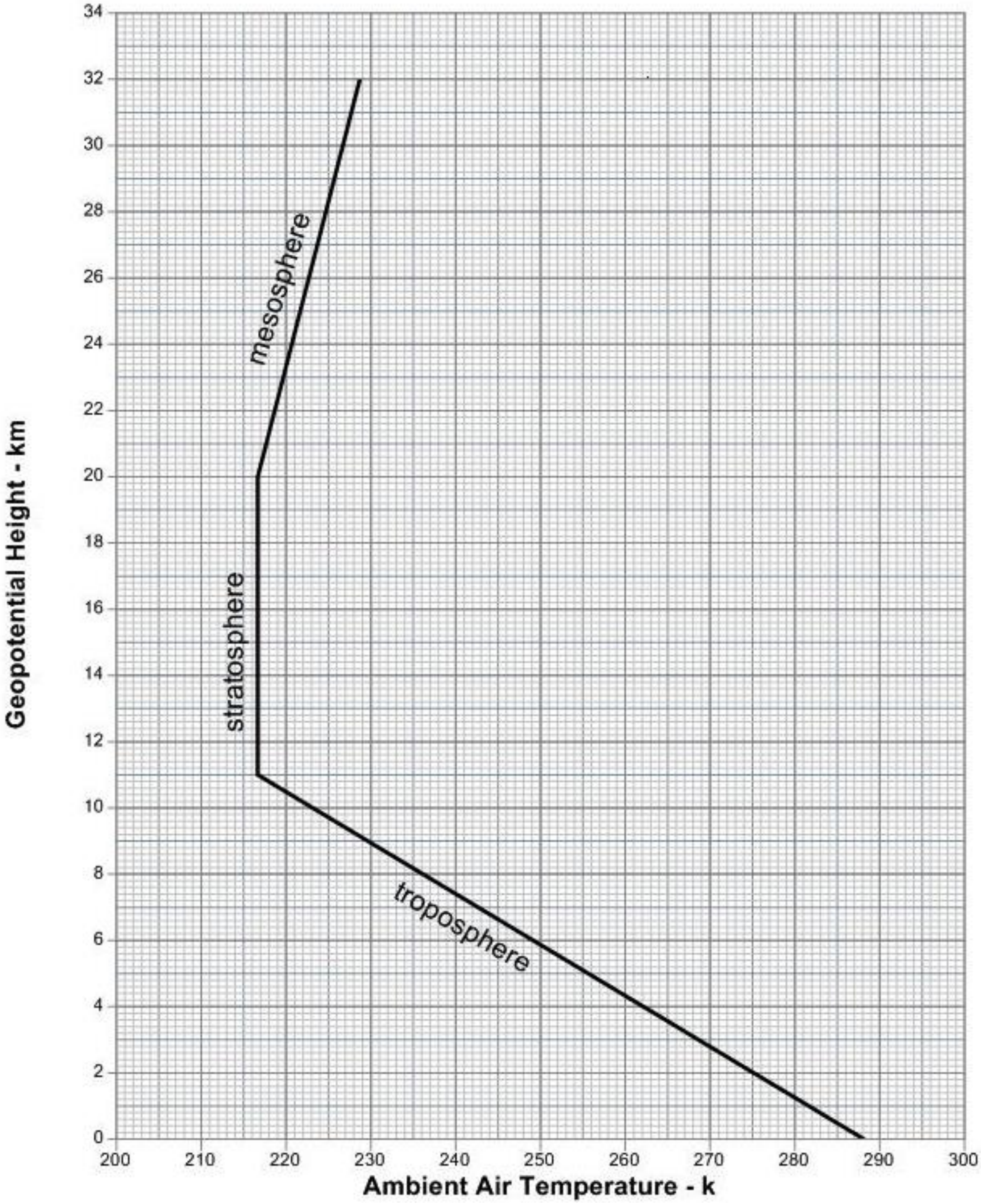

Figure 2 Standard Day Ambient Air Temperature Profile

Table 5 summarizes the ambient air temperature models for the two lowest segments of the 1976 U.S. standard atmosphere and for the 1993 ICAO international standard atmosphere. The troposphere, from sea level through 11,000 geopotential meters, has a linearly decreasing ambient air temperature with increasing geopotential height. The stratosphere, from 11,000 through 20,000 geopotential meters, has a constant ambient air temperature, 216.65 K. The constants in table 5 define the ambient air temperature variations with geopotential height for these standard atmosphere models. These models are also known as a standard day temperature profile. The standard day temperature profile for the first three segments of the atmosphere is presented in figure 2.

Table 5 Assumed Standard Day Ambient Air Temperatures

Segment (n/d)	Geopotential Height Range (km)		Ambient Air Temperature (K)		Temperature Lapse Rate (K/km)
	Bottom	Top	Bottom	Top	
Troposphere	0	11	288.15	216.65	-6.50
Statosphere	11	20	216.65	216.65	0.00

Notes: 1. For the purposes of this handbook, these ambient air temperatures and the associated temperature lapse rates are assumed to be exact.
2. A kilometer is equal to 1,000 meters.
3. Abbreviations, acronyms, and symbols are defined in appendix H.

Solving for a Linearly Varying Ambient Air Temperature:

The lowest segment of the atmospheric model, the troposphere, is between sea level and 11,000 meters of geopotential height above mean sea level and is modeled with a linearly decreasing ambient air temperature with increasing geopotential height. The ambient air temperature linearly decreases from 15.0-degrees Celsius (C), 288.15 K, at sea level to -56.5 degrees C, 216.65 K, at 11,000 geopotential meters, table 6. The temperature lapse rate is assumed to be exactly -6.50 K per kilometer or -0.00650 K per geopotential meter.

Table 6 Ambient Air Temperatures in the Troposphere for the 1976 U.S. Standard Atmosphere

Units (deg)	Ambient Air Temperature	
	Sea Level	11,000 meters
Fahrenheit (F)	59.00	-69.70
Celsius (C)	15.00	-56.50
Rankine (R)	518.67	389.97
Kelvin (K)	288.15	216.65

Notes: 1. For the purposes of this handbook, all of these temperature values are assumed to be exact.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

Equation 17 will now be solved for a linearly varying ambient air temperature with changes in geopotential height, the troposphere in this case. That temperature variation is modeled in equation 18.

Where:

1. T_0 = ambient air temperature at sea level on a standard day
2. a = ambient air temperature lapse rate with geopotential altitude
3. H_0 = 0 = sea level
4. H = a geopotential height above sea level

5. T = the ambient air temperature at a height of H geopotential feet

The magnitude of the temperature lapse rate in SI units is:

$$a = (216.65 – 288.15)\ K/11,000\ (meters)$$

$$a = -0.006500\ (K/meter)$$

$$\int \left(\frac{dP}{P}\right) = -g_0\left(\frac{1}{R}\right) \int \left(\frac{1}{T}\right) dH \qquad (17)$$

$$T = T_0 + a\,(H - H_0) \qquad (18)$$

$$\int_0^1 \left(\frac{dP}{P}\right) = -g_0\left(\frac{1}{R}\right) \int_0^1 \left\{\frac{1}{[T_0+a(H-H_0)]}\right\} dH \qquad (19)$$

$$\int_0^1 \frac{dP}{[0+1\ (P)]} = -g_0\left(\frac{1}{R}\right) \int_0^1 \left\{\frac{1}{[T_0+a(H-H_0)]}\right\} dH$$

From calculus:

$$\int_0^1 \frac{dx}{(u+vx)} = \frac{1}{v} \ln\,(u + vx)\ \Big|_1 - \frac{1}{v} \ln\,(u + vx)\Big|_0 \qquad (20)$$

$$\ln(u) – 1n\,(v) = \ln\left(\frac{u}{v}\right) \qquad (21)$$

Comparing the left side of equation 20 to the left side of equation 19:

$$u = 0$$
$$v = 1$$

$$\int_0^1 \left(\frac{dP}{P}\right) = \int_0^1 \left[\frac{dP}{0+(1P)}\right] = \left(\frac{1}{1}\right) 1n[0 + (1P)] - \left(\frac{1}{1}\right) 1n[0 + (1P_0)]$$

$$\int_0^1 \left(\frac{dP}{P}\right) = 1n(P) – 1n(P_0)$$

$$\int_0^1 \left(\frac{dP}{P}\right) = 1n\left(\frac{P}{P_0}\right)$$

Comparing the right side of equation 20 to the right side of equation 19:

$$-g_0 \left(\frac{1}{R}\right) \int_0^1 \left\{\frac{1}{[T_0+a(H-H_0)]}\right\} dH = -g_0 \left(\frac{1}{R}\right) \int_0^1 \left\{\frac{1}{[(T_0-aH_0)+aH]}\right\} dH$$

$$\int \frac{dx}{(u+vx)} = \frac{1}{v}\, 1n(u+vx) \qquad (20)$$

$$u = (T_0 - aH_0)$$
$$v = a$$

$$-g_0\left(\frac{1}{R}\right)\int_0^1\left\{\frac{1}{[T_0+a(H-H_0)]}\right\}dH = -g_0\left(\frac{1}{R}\right)\left(\frac{1}{a}\right)\Big(\Big\{1n\Big[(T_0\text{-}aH_0) + aH\Big]+$$

$$-1n\Big[(T_0\text{-}aH) + aH\Big]\Big\}\Big)$$

$$-g_0\left(\frac{1}{R}\right)\int_0^1\left\{\frac{1}{[T_0+a(H-H_0)]}\right\}dH = -g_0\left(\frac{1}{R}\right)\left(\frac{1}{a}\right)\Big\{1n\Big[T_0+a(H\text{-}H_0)\Big] - 1n(T_0)\Big\}$$

$$-g_0\left(\frac{1}{R}\right)\int_0^1\left\{\frac{1}{[T_0+a(H-H_0)]}\right\}dH = -g_0\left(\frac{1}{Ra}\right)1n\left\{\frac{[T_0+a(H-H_0)]}{T_0}\right\}$$

Where:

T	=	ambient air temperature
T_0	=	ambient air temperature at the bottom of the segment, sea level in this case
a	=	temperature lapse rate with geopotential height
H	=	geopotential height above the bottom of the segment, sea level in this case
H_0	=	geopotential height at the bottom of the segment, zero (sea level) in this case

For the first segment of the atmosphere, the troposphere:

$$\ln\left(\frac{P}{P_0}\right) = -\left(\frac{g_0}{Ra}\right)\ln\left[\frac{T_0+a(H-H_0)}{T_0}\right] \tag{22}$$

Solving for the ambient air pressure, P:

$$\boxed{P = P_0\left[1+\left(\frac{a}{T_0}\right)(H-H_0)\right]^{\left[\frac{-g_0}{(Ra)}\right]}} \tag{23}$$

Or, solving for the pressure altitude, H_p:

$$\boxed{\frac{P}{P_0} = \left[1+\left(\frac{a}{T_0}\right)(H-H_0)\right]^{\left[\frac{-g_0}{(Ra)}\right]}} \tag{24}$$

$$\left(\frac{P}{P_0}\right)^{\left[\frac{-(Ra)}{g_0}\right]} = 1+\left(\frac{a}{T_0}\right)(H\text{-}H_0) \tag{25}$$

$$\left(\frac{a}{T_0}\right)(H\text{-}H_0) \quad = \quad \left(\frac{P}{P_0}\right)^{\left[\frac{-(Ra)}{g_0}\right]} -1 \tag{26}$$

$$(H\text{-}H_0) \quad = \quad \left[\left(\frac{P}{P_0}\right)^{\left[\frac{-(Ra)}{g_0}\right]}\right]\left(\frac{T_0}{a}\right) \tag{27}$$

$$\boxed{H \quad = \quad H_0 + \left[\left(\frac{P}{P_0}\right)^{\left(\frac{-Ra}{g_0}\right)} - 1\right]\left(\frac{T_0}{a}\right)} \tag{28}$$

Here we transition from a geopotential height, H, in equation 28, to a pressure altitude, H_p, in equation 29. Equation 29 represents the defining equation for pressure altitude in the troposphere. Although equation 29 has two ambient air temperature terms, T_0 (the sea level, standard day temperature) and a (the standard day ambient air temperature lapse rate with geopotential height); pressure altitude, H_p, is solely a function of the ambient air pressure. The six terms are all constants and are independent of the test day ambient air temperatures:

1. H_0 = 0 (sea level for the troposphere)
2. P_0 = standard day ambient air pressure at sea level
3. R = gas constant for dry air
4. g_0 = the reference acceleration due to the Earth's gravity at sea level
5. a = the standard day ambient air temperature lapse rate with geopotential height
6. T_0 = the standard day ambient air temperature at sea level

Equation 29 and later equations 32 and 34 are valid relationships between pressure altitudes and ambient air pressures for all test day ambient air temperatures in the troposphere. This is true, even if the test day ambient air pressure at sea level is not equal to the standard day value. (For that case, the test day pressure altitude at sea level will not be zero. However, the test day pressure altitude will be zero where the test day ambient air pressure is equal to P_0.) The equations are also valid relationships between geopotential altitudes and ambient air pressures, but only if the test day ambient air pressure and temperature at sea level are equal to the standard day values and the test day ambient air temperature lapse rate is equal to the standard day value.

The constants for the troposphere are presented in table 7 for the International System of Units, the SI or metric system, and in table 8 for the U.S. customary units. Table 9 presents other frequently used values for the standard atmospheric pressure at sea level.

For $H_0 = 0$:

$$\boxed{H_p \quad = \quad \left[\left(\frac{P}{P_0}\right)^{\left(\frac{-Ra}{g_0}\right)} - 1\right]\left(\frac{T_0}{a}\right)} \tag{29}$$

The concept presented above is absolutely critical to the understanding of Pitot statics. The following are presented again for emphasis:

1. Equations 23, 28, and 29 were developed for an atmospheric segment with a linearly varying ambient air temperature with geopotential altitude.

2. Equations 23 and 28 document relationships between ambient air pressure, P, and geopotential altitude, H.

3. For the special case of the standard day ambient air temperature at sea level, T_0, and the standard day temperature lapse rate, a; pressure altitude, H_p, is defined to be equal to the geopotential altitude, H.

4. The relationships between ambient air pressure, P, and pressure altitude, H_p, are defined by equations 23 and 29 using the standard day values of the temperature lapse rate, a, and the standard day ambient air temperature, T_0. After the substitution of the constants for T_0 and for a, the equations are valid for any test day values of ambient air temperature.

5. Pressure altitude is defined as a point in the atmosphere at which an ambient air pressure exists. In general, except for the special case of a standard day; there is no unique relationship between pressure altitude and geopotential or geometric altitude.

Table 7 Constants for the Troposphere Model (SI Units)

Parameter	Symbol	Value	Units
Ambient Air Pressure at Sea Level	P_0	101,325	$kg/(m \cdot sec^2)$ or pascals
Ambient Air Temperature at Sea Level	T_0	288.15	K
Temperature Lapse Rate	a	-0.00650	K/m
Pressure Altitude at Sea Level	H_0	0.00	m
Reference Acceleration due to Gravity	g_0	9.80665	m/sec^2
Specific Gas Constant for Dry Air	R	287.052 87	$(m/sec)^2/K$

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

Table 8 Constants for the Troposphere Model (U.S. Customary Units)

Parameter	Symbol	Value	Units
Ambient Air Pressure at Sea Level	P_0	2116.216 7	lb/ft^2
		1013.25	millibars
		29.921 252 4	in Hg
		14.695 95	psia
Ambient Air Temperature at Sea Level	T_0	518.67	deg R
Temperature Lapse Rate	a	-0.003 566 16	deg R/ft
Pressure Altitude at Sea Level	H_0	0.00	ft
Reference Acceleration due to Gravity	g_0	32.174 049	ft/sec^2
Specific Gas Constant for Dry Air	R	3089.812 77	$(ft/sec)^2/K$
		1716.562 654	$(ft/sec)^2/(deg\ R)$

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

Table 9 Reference Ambient Air Pressures at Sea Level

Numerical Value	Units
101,325.000 (exact)	newtons per square meter or pascals (P_a)
1013.250 (exact)	millibars (mb) or hectopascals (hP_a)
1.013 250 (exact)	bar
29.921 252 4	inches of mercury
2116.216 7	pounds per square foot
14.695 949	pounds per square inch
760.000 (exact)	torr (millimeters of mercury)

Notes:
1. Per table 11 on page 20 of the *U.S. Standard Atmosphere, 1976*, reference 1, the conversion for inches of mercury from millibars is to divide by 33.863 89 or to multiply by 0.029 529 98. (This conversion assumes an ambient air temperature of 32 degrees Fahrenheit.)
2. The conversion from pascals to pounds per square foot is to divide by 47.880 26 or to multiply by 0.020 885 434. These conversions were from page 66 of the National Institute of Standards and Technology (NIST) *Guide for the Use of the International System of Units (SI)*, reference 13.
3. The number of significant figures in this handbook is not intended to imply an ability to measure. At best, we can calibrate ambient air pressures sensors to ±0.001 or 0.002 inch of mercury in a laboratory and maybe ±0.01 inch of mercury when uncertainties in flight test-determined position error corrections are considered.
4. Abbreviations, acronyms, and symbols are defined in appendix H.

For the troposphere, from sea level through 11,000 geopotential meters, the end points are 0 (sea level) and 1 (11,000 meters) because it is the first atmospheric segment. By convention, the subscript $_0$ is replaced by the subscript $_{SL}$.

The equations for the troposphere in SI units from equations 24 and 29 are:

$$\boxed{\delta = P/P_{SL} = \{1 - [(2.255\,769\,587 \times 10^{-5})H_p]\}^{5.255\,880}} \quad (30)$$

$$H_p = (\delta^{0.190\,263\,1} - 1)(-44{,}330.769\,23) \quad (31)$$

$$H_p = (44{,}330.77)\,(1 - \delta^{0.190\,263\,1}) \qquad (32)$$

Where:

H_p	=	pressure altitude, meters
δ	=	ambient air pressure ratio, dimensionless

The equivalent equations using geopotential feet vice geopotential meters are:

$$\delta = \{1 - [(6.875\,585\,7 \times 10^{-6})\,H_p]\}^{5.255\,880} \qquad (33)$$

$$H_p = (145{,}442.16)\,(1 - \delta^{0.190\,263\,1}) \qquad (34)$$

Note: Since the exponents are dimensionless, they are unchanged when switching from meters to feet.

Solving for a Constant Ambient Air Temperature:

$$\int \left(\frac{dP}{p}\right) = -\left(\frac{g_0}{R}\right) \int \left(\frac{1}{T}\right) dH \qquad (16)$$

$$\int_1^2 \left(\frac{dP}{P}\right) = -g_0\left(\frac{1}{RT}\right) \int_1^2 dH \qquad (35)$$

Like in the previous section, equations 20 and 21 will be used to solve equation 35. From the previous section:

$$\int_1^2 \left(\frac{dP}{P}\right) = 1n\left(\frac{P}{P_1}\right)$$

From calculus:

$$\int_1^2 dH = (H - H_1)$$

Thus:

$$\ln\left(\frac{P}{P_1}\right) = \left\{-\left(\frac{g_o}{RT}\right)(H - H_1)\right\} \qquad (36)$$

$$\frac{P}{P_1} = e^{\left[-\left(\frac{g_0}{RT}\right)(H - H1)\right]} \qquad (37)$$

$$P = P_1 e^{\left[-\left(\frac{g_0}{RT}\right)(H - H1)\right]} \quad (38)$$

Or, recalling that $\delta = \frac{P}{P_{SL}}$, equations 8 and 9,

$$\boxed{\delta = \delta_1 e^{\left[-\left(\frac{g_0}{RT}\right)(H - H1)\right]}} \quad (39)$$

Where:

P_1 = ambient air pressure at the bottom of the second segment

H_1 = geopotential height at the bottom of the second segment, 11,000 meters

δ_1 = ambient air pressure ratio at the bottom of the second segment

$$\ln\left(\frac{P}{P_1}\right) = -\left(\frac{g_0}{RT}\right)(H - H_1) \quad (36)$$

$$(H-H_1) = -\left(\frac{RT}{g_0}\right)\ln\left(\frac{P}{P_1}\right) \quad (40)$$

$$\boxed{H = H_1 - \left(\frac{RT}{g_0}\right)\ln\left(\frac{P}{P_1}\right)} \quad (41)$$

The constants for the stratosphere are presented in table 10 for the SI system and in table 11 for the U.S. customary units. The resulting equations from equations 39 and 41 are equations 42 through 44 for the SI units:

$$\delta = (0.223\ 360\ 9)e^{-\left[(1.576\ 885\ 2x10^{-4})(H_p - 11{,}000)\right]} \quad (42)$$

$$\boxed{\delta = (0.223\ 360\ 9)e^{\left[(1.734\ 573\ 7) - (1.576\ 885\ 2x10^{-4})H_p\right]}} \quad (43)$$

And

$$\boxed{H_p = 11{,}000 - \{(6341.6157)\ln[P/(22{,}632.043)]\}} \quad (44)$$

for H_p in meters and P in kg/(m·sec^2) or pascals.

Table 10 Constants for the Stratosphere Model (SI Units)

Parameter	Symbol	Units	Value
Ambient Air Pressure at 11,000 Meters Geopotential Height	P_1	$kg/(m \cdot sec^2)$ or pascals	22,632.043
Ambient Air Temperature	T	K	216.65
Geopotential Height at the Bottom of the Stratosphere	H_1	m	11,000
Reference Acceleration due to Gravity	g_0	m/sec^2	9.80665
Specific Gas Constant for Dry Air	R	$(m/sec)^2/K$	287.052 87

Notes: 1. P_1 was calculated using P_0 = 101,325 pascals and δ = 0.223 360 9.

2. The symbol T requires no subscript because the ambient air temperature is constant in the stratosphere on a standard day. Therefore, T_1 and T_2 and all the ambient air temperatures between 11,000 and 20,000 geopotential meters are the same on a standard day.

3. Abbreviations, acronyms, and symbols are defined in appendix H.

Table 11 Constants for the Stratosphere Model (U.S. Customary Units)

Parameter	Symbol	Units	Value
Ambient Air Pressure at 11,000 Meters Geopotential Height	P_1	lb/ft^2	472.680
		millibars	226. 320
		in Hg	6.683 238
Ambient Air Temperature	T	R	389.97
Geopotential Height at the Bottom of the Stratosphere	H_1	ft	36,089. 239
Reference Acceleration due to Gravity	g_0	ft/sec^2	32.174 049
Specific Gas Constant for Dry Air	R	$(ft/sec)^2/K$	3089.812 77
		$(ft/sec)^2/deg\ R)$	1716.562 654

Notes: 1. P_1 was calculated using P_0 = 2116.216 6 (lb/ft^2) or 1013.250 (millibars) or 29.921 252 (in Hg) and δ = 0.223 360 9.

2. Abbreviations, acronyms, and symbols are defined in appendix H.

The equivalent equations to equations 43 and 44 for the geopotential height in feet are equations 45 and 46:

$$\boxed{\delta \quad = \quad (0.223\ 360\ 9)\ e^{\{[(4.806\ 346\ 1) \times 10^{-5}](36{,}089.239 - H_p)\}}} \tag{45}$$

$$\boxed{H_p \quad = \quad 36{,}089.239 - (20{,}805.826) \ln [(4.477\ 077\ 4)\ \delta]} \tag{46}$$

Equations 33, 34, 45 and 46 accurately match the tables in references 1 and 3, well within the required accuracies for flight test.

PRESSURE ALTITUDE AND AMBIENT AIR PRESSURE

For a given set of units there are unique equations expressing the relationships between pressure altitude and ambient air pressure or the ambient air pressure ratio, δ. For example, using geopotential feet.

For the troposphere, below 36,089 feet, use the previous equations 33 and 34.

$$\boxed{\delta = \{1 - [(6.875\ 585\ 7 \times 10^{-6})\ H_p]\}^{5.255\ 880}} \tag{33}$$

$$\boxed{H_p = (145{,}442.16)(1-\delta^{0.1902631})} \tag{34}$$

For the stratosphere, between 36,089 and 65,617 feet, use the previous equations 45 and 46.

$$\boxed{\delta = (0.223\ 360\ 9)e^{\{[(4.806\ 346\ 1) \times 10^{-5}](36{,}089.239 - H_p)\}}} \tag{45}$$

$$\boxed{H_p = (36{,}089.239) - (20{,}805.826)\ \ln\ [(4.477\ 077\ 4)\ \delta]} \tag{46}$$

Notice, there are no ambient air temperature inputs in equations 33, 34, 45, or 46. They can be solved without a knowledge of the ambient air temperature. Temperature profiles as a function of geopotential heights were used in the development of a standard day atmospheric model; however, the relationships between pressure altitude and ambient air pressure are completely independent of either test day or reference day ambient air temperatures. The non-standard day relationships between geometric height, pressure altitude, altimeter setting, and test day ambient air temperatures are outside the scope of this handbook.

DENSITY ALTITUDE

Although not directly connected to the discussion of pressure altitude, calibrated airspeed, and Mach number; a short section concerning density altitude is included for completeness. Its development will parallel that used for pressure altitude.

Density altitude is used with piston-powered, propeller-driven aircraft and turboprop aircraft. It is not, in general, used with turbojet- or turbofan-powered aircraft.

STANDARD DAY

Pressure Altitude and Ambient Air Pressure:

Pressure altitude is exactly equal to geopotential height for a standard day. There are also unique relationships between pressure altitude and ambient air pressure on a standard day.

For the troposphere using geopotential feet:

$$\boxed{\delta = \{1 - [(6.875\ 585\ 7 \text{ x } 10^{-6})\ H_p]\}^{5.255\ 880}} \qquad (33)$$

$$\boxed{H_p = (145{,}442.16)(1-\delta^{\ 0.1902631})} \qquad (34)$$

For the stratosphere, using geopotential feet:

$$\boxed{\delta = (0.223\ 360\ 9)e^{\{[(4.806\ 346\ 1) \text{ x } 10^{-5}](36{,}089.239 - H_p)\}}} \qquad (45)$$

$$\boxed{H_p = (36{,}089.239) - (20{,}805.826) \ln [(4.477\ 077\ 4)\ \delta]} \qquad (46)$$

Pressure Altitude and Ambient Air Temperature:

Ambient air temperature for a standard day is uniquely defined by a series of linear relationships, figure 2. The standard day relationships can be defined in terms of pressure altitude or geopotential height since they are identical for a standard day.

For the troposphere using geopotential feet and Kelvin for the ambient air temperature:

$$\boxed{T = T_0 + a(H-H_0)} \qquad (18)$$

Substituting 288.15 K for T_0, the standard day ambient air temperature at sea level, zero (sea level) for H_0, and the ambient air temperature lapse rate for the troposphere into equation 18 produces equation 47.

$$\boxed{T = 288.15 - (0.001\ 981\ 200)H_p} \qquad (47)$$

Dividing by T_0, the ambient air temperature at sea level on a standard day, produces an equation for the ambient air temperature ratio, θ.

$$\theta = T/T_0 = 1 - (a/T_0)\, H_p \tag{48}$$

$$\theta = 1 - [(6.875\ 585\ 7) \times (10^{-6})]H_p \tag{49}$$

Notice the similarity between equation 49 and equation 33.

$$\boxed{\delta = \{1 - [(6.875\ 585\ 7 \times 10^{-6})\ H_p]\}^{5.255\ 880}} \tag{33}$$

The ambient air temperature is constant in the stratosphere for a standard day.

$$T = 216.65\ K$$

$$\theta = T/T_{SL} = 216.65/288.15 = 0.751\ 865\ 3$$

Density Altitude:

Recalling the non-dimensional equation for a perfect gas, equation 9:

$$\delta = \sigma\, \theta \tag{9}$$

$$\sigma = \delta/\theta \tag{50}$$

For the troposphere using geopotential feet and using equations 33, 49, and 50:

$$\boxed{\delta = \{1 - [(6.875\ 585\ 7 \times 10^{-6})\ H_p]\}^{5.255\ 880}} \tag{33}$$

$$\boxed{\theta = 1 - [(6.875\ 585\ 7) \times (10^{-6})]H_p} \tag{49}$$

$$\boxed{\sigma = \delta/\theta} \tag{50}$$

$$\sigma = \frac{\{1-[(6.875\ 585\ 7 \times 10^{-6})H_p]\}^{5.255\ 880}}{\{1-[(6.875\ 585\ 7) \times (10^{-6})]H_p\}} \tag{51}$$

$$\boxed{\sigma = \{1 - [(6.875\ 585\ 7 \times 10^{-6})\ H_\sigma]\}^{4.255\ 880}} \tag{52}$$

$$H_\sigma = 145{,}442.16\left[1 - \sigma^{(0.234\ 969\ 03)}\right]$$

Equation 52 relates geopotential height (and pressure altitude and density altitude) to the ambient air density ratio in the troposphere on a standard day.

For the stratosphere, using equations 45 and 50, and the ambient air temperature ratio for a standard day:

$$\boxed{\delta = (0.223\ 360\ 9)e^{\{[(4.806\ 346\ 1)\ x\ 10^{-5}](36{,}089.239 - H_p)\}}} \quad (45)$$

$$\boxed{\sigma = \delta/\theta} \quad (50)$$

Substituting equation 45 for δ and 0.751 865 3 for θ into equation 50 results in equation 53.

$$\sigma = \frac{(0.223\ 360\ 9)e^{\{[(4.806\ 346\ 1) x\ 10^{-5}](36{,}089.239 - H_p)\}}}{(0.751\ 865\ 3)} \quad (53)$$

$$\boxed{\sigma = (0.297\ 075\ 6)e^{\{[(4.806\ 346\ 1)\ x\ 10^{-5}](36{,}089.239 - H_p)\}}} \quad (54)$$

Equations 52 and 54 relate the standard day ambient air density ratios and the geopotential heights (and the pressure altitudes). Note that for a standard day geopotential height, pressure altitude, and density altitude are identical.

NON-STANDARD DAY

Now, by definition, we change the geopotential heights to density attitudes and remove the restriction of a standard day. The following statement is made by similarity with the approach used for defining pressure altitude:

> Density altitude is a point in the atmosphere at which a density exists. Given an ambient air density ratio, σ; the corresponding density altitude may be calculated using equations 52 or 54 (based on the value of the ambient air density ratio).

If the test day ambient air density ratio is greater than 0.297 075 68, use equation 52. If it is less than 0.297 075 68 and greater than 0.07186, use equation 54.

([TOTAL AIR PRESSURE]/[AMBIENT AIR PRESSURE]) RATIO AND MACH NUMBER

Equations 55 and 56 (relating Mach number and the ratio of the total air pressure to the ambient air pressure) and later equation 86 (relating Mach number and the ratio of the total air temperature to the ambient air temperature) and equation 74 (relating ambient air temperature and the local speed of sound) are introduced into the handbook without derivations. Their extensive derivations are presented in most college level gas dynamics textbooks and in some college level thermodynamics and aerodynamics textbooks, references 14 through 21.

The subsonic relationship between total air pressure, ambient air pressure, and Mach number are equations 56 and 60.

$$\boxed{\left(\frac{P_T}{P_a}\right) = \left\{1 + \left[\frac{(\gamma-1)}{2}\right] M^2\right\}^{\left[\frac{\gamma}{\gamma-1}\right]}} \tag{55}$$

For $\gamma = 1.400$:

$$\boxed{\left(\frac{P_T}{P_a}\right) = (1 + 0.2\ M^2)^{3.5}} \tag{56}$$

Where:

P_T	=	total air pressure
P_a	=	ambient air pressure
M	=	Mach number
0.2	=	$\frac{(\gamma-1)}{2}$ for $\gamma = 1.400$
3.5	=	$\frac{\gamma}{(\gamma-1)}$ for $\gamma = 1.400$

Solving equation 56 for Mach number:

$$\left(\frac{P_T}{P_a}\right)^{1/3.5} = (1 + 0.2\ M^2) \tag{57}$$

$$0.2\ M^2 = \left(\frac{P_T}{P_a}\right)^{1/3.5} - 1 \tag{58}$$

$$M^2 = 5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right] \tag{59}$$

$$\boxed{M = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{60}$$

Where:

$$1/3.5 \quad = \quad 0.285\ 714\ 286 \tag{61}$$

Equation number 60 is frequently written in another form involving differential pressure, q_c.

Differential pressure, $P_T - P_a$, is the compressible equivalent of the incompressible dynamic pressure.

$$q_c \quad = \quad P_T - P_a \tag{62}$$

$$P_T \quad = \quad P_a + q_c \tag{63}$$

Substituting equation number 63 for P_T into equation number 60 and rearranging the terms.

$$M \quad = \quad \left(5\left\{\left[\frac{(P_a+q_c)}{P_a}\right]^{1/3.5} -1\right\}\right)^{0.5} \tag{64}$$

$$\frac{(P_a+q_c)}{P_a} = 1 + \left(\frac{q_c}{P_a}\right) = \left(\frac{q_c}{P_a}\right) + 1$$

$$\boxed{M \quad = \quad \left(5\left\{\left[\left(\frac{q_c}{P_a}\right) +1\right]^{1/3.5} -1\right\}\right)^{0.5}} \tag{65}$$

Note: q_c is often referred to in technical references as the compressible dynamic pressure, q_c, or as the differential pressure, q_d.

Solving equation 56 for q_c/P_a:

$$\left(\frac{P_T}{P_a}\right) \quad = \quad (1 + 0.2\ M^2)^{3.5} \tag{56}$$

$$P_T \quad = \quad P_a + q_c \tag{63}$$

$$\frac{(q_c+P_a)}{P_a} \quad = \quad \frac{q_c}{P_a} + \frac{P_a}{P_a} \quad = \quad \frac{q_c}{P_a} + 1 = (1+0.2M^2)^{3.5} \tag{66}$$

$$\boxed{\frac{q_c}{P_a} \quad = \quad (1 + 0.2M^2)^{3.5} -1} \tag{67}$$

$$q_c = P_a\left[(1+0.2M^2)^{3.5}-1\right] \quad (68)$$

$$\delta = \frac{P_a}{P_{SL}} \quad (69)$$

$$P_a = P_{SL}\delta \quad (70)$$

$$P_{SL} = \frac{P_a}{\delta} \quad (71)$$

Replacing P_a in equation 68 with $P_{SL}\delta$ from equation 70:

$$\boxed{q_c = P_{SL}[(1 + 0.2M^2)^{3.5} - 1]\,\delta} \quad (72)$$

Notice in equations 55 through 72 that there are no ambient air temperature terms. The only terms are Mach number and forms of pressure.

Another equation frequently used for Mach number and its definition is:

$$M = \frac{V_T}{a} \quad (73)$$

Where:

M = Mach number

V_T = true airspeed

a = speed of sound

It is generally known that both true airspeed and speed of sound are functions of ambient air temperature. It will be shown in later sections of this handbook that both are directly proportional to the square root of the ambient air temperature. Thus, when the ratio $\frac{V_T}{a}$ is calculated, the ambient air temperature terms cancel.

Although both true airspeed and speed of sound are functions of the ambient air temperature, Mach number can be described in terms of only ambient and total air pressure. This allows Mach number to be calculated knowing only the total and the ambient air pressures. The functions of temperature cancel out when the ratio of the two velocities is determined.

LOCAL SPEED OF SOUND

An equation for speed of sound from gas dynamics is:

$$a = (\gamma RT)^{½} \tag{74}$$

Where:

a	=	local speed of sound
γ	=	1.400 for dry air at reasonable temperatures
R	=	gas constant with units compatible with the temperature units
T	=	ambient air temperature in absolute units, either K or degrees Rankine

Since equation number 74 is assumed to be valid throughout the atmosphere, it is valid at sea level on a standard day.

$$a_{SL} = (\gamma RT_{SL})^{½} \tag{75}$$

Dividing equation number 74 by equation number 75 produces:

$$\frac{a}{a_{SL}} = \frac{(\gamma RT)^{½}}{(\gamma RT_{SL})^{½}} = \left(\frac{T}{T_{SL}}\right)^{½} \tag{76}$$

Introducing the ambient air temperature ratio, θ, and substituting into equation number 76:

$$\theta = \frac{T}{T_{SL}} \tag{77}$$

$$\boxed{\frac{a}{a_{SL}} = \theta^{½}} \tag{78}$$

$$a = a_{SL}\theta^{½} \tag{79}$$

The speed of sound at sea level on a standard day is 340.294 meters per second as defined in table 10 on page 20 of reference 1. That is equivalent to 1116.450 feet per second. The equivalent value in knots is:

$$a_{SL} = 340.294 \text{ (m/sec) } 3600 \text{ (sec/hr)/}1852 \text{ (m/nautical mile)}$$

$$a_{SL} = 661.478\ 617\ 7 \text{ (knots)}$$

$$a_{SL} = 340.294 \text{ (m/sec)/}[0.3048 \text{ (m/ft)}]$$

$$a_{SL} = 1116.450\ 131 \text{ (ft/sec)}$$

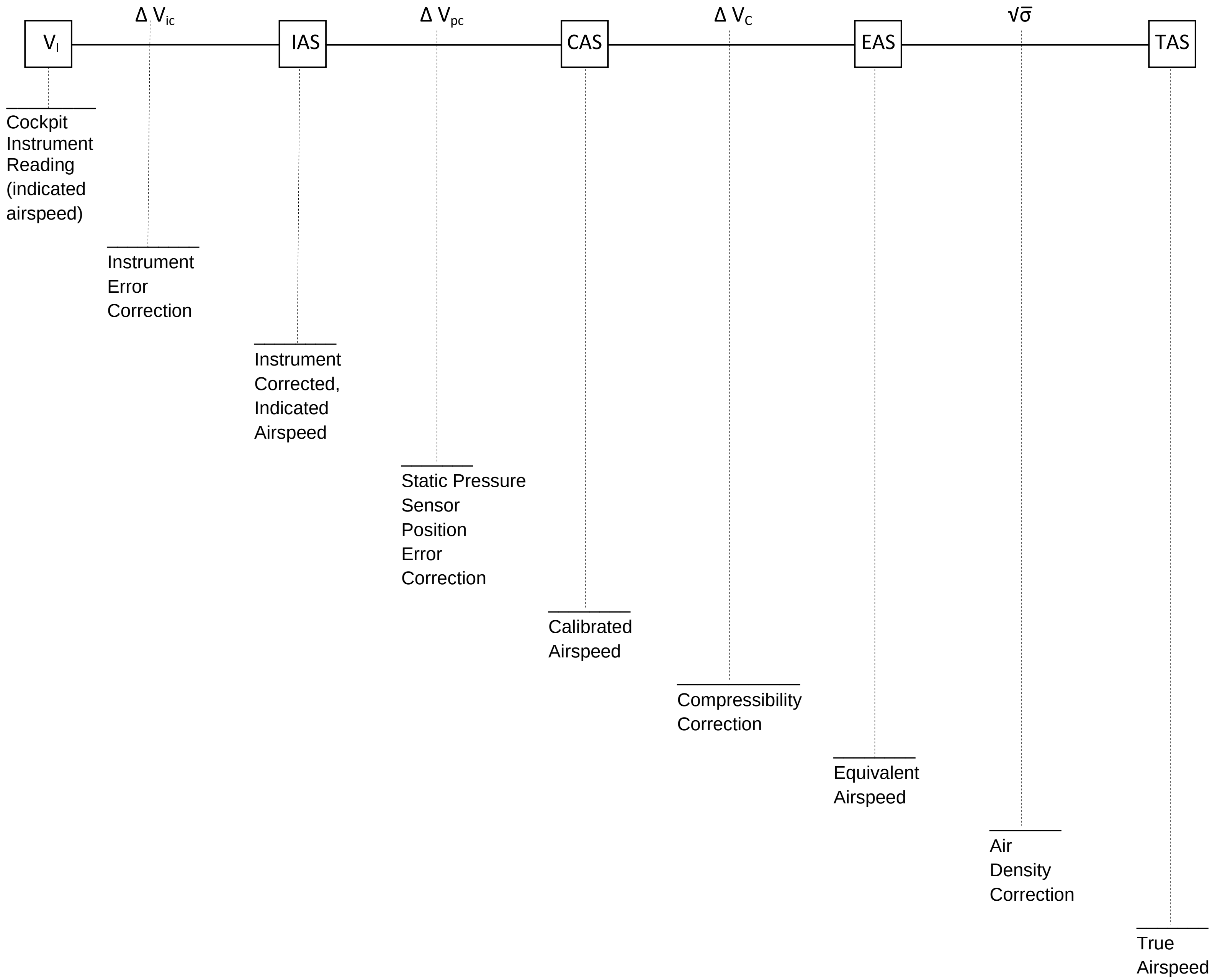

Figure 3 Airspeed Corrections

TRUE AIRSPEED (HISTORICALLY)

True airspeed has historically, since 1925 (references 22, 23, and 24), been determined in the following manner illustrated in figure 3:

1. Read a value off the mechanical airspeed indicator, indicated airspeed, V_i.

2. Correct the reading for known mechanical errors in the instrument to create an instrument corrected, indicated airspeed.

$$V_{ic} = V_i + \Delta V_{ic} \tag{80}$$

Note: The symbol V_I is sometimes used in the place of V_{ic} for instrument corrected, indicated airspeed.

3. Correct for errors in the measurement of ambient air pressure to create a calibrated airspeed. (The static pressure at the static port was not equal to the freestream ambient air pressure.)

$$V_c = V_i + (\Delta V_{ic} + \Delta V_{pc}) \tag{81}$$

4. Correct for 'compressibility' to create an equivalent airspeed.

$$V_e = V_i + (\Delta V_{ic} + \Delta V_{pc} + \Delta V_c) \tag{82}$$

5. Correct for non-standard day ambient air temperature, to create a true airspeed.

$$V_T = \frac{V_e}{\sqrt{\sigma}} \tag{83}$$

Where:

V_i	=	The value read off the dial, indicated or instrument airspeed
ΔV_{ic}	=	The laboratory determined correction to account for manufacturing defects and mechanical wear
V_{ic}	=	The 'instrument corrected' value
ΔV_{pc}	=	The 'position error' correction correcting for the error in the measured static pressure relative to the freestream ambient air pressure. (The label 'position error' correction comes from the idea that the difference in pressures existed because the pressure was sensed at the wrong position on the aircraft.)
V_c	=	Calibrated airspeed: (In this usage, 'calibrated' refers to the two corrections that have been applied.) Calibrated airspeed represents the true airspeed that would have existed at sea level on a standard day with the same difference between the sensed total and static pressures.

ΔV_c = A generic, aircraft independent, correction converting the calibrated airspeed into an equivalent airspeed, figure 4.
NOTE: Figure 4 was created using equations 129 or 154, and either equations 33 or 45.

Ve = Equivalent airspeed: The airspeed equivalent to a calibrated airspeed at sea level corresponding to a differential pressure, P_T-P_a. In addition, the airspeed equivalent to a true airspeed at sea level corresponding to the same differential pressure for the special case of a standard day at sea level. For the special case of sea level, standard day; calibrated airspeed, equivalent airspeed, and true airspeed are identical in magnitude.

WARNING: The aerospace industry is not consistent when using this correction. Some add a negative value while others subtract a positive value. Equivalent airspeed is always less than calibrated airspeed for pressure altitudes above sea level.

$\sqrt{\sigma}$ = square root of the ambient air density ratio, ρ/ρ_{SL}

V_T = true airspeed, the speed of the aircraft with respect to the air mass it is traveling through

This handbook presents a different approach to calculating these airspeeds if total air pressure, ambient air pressure, and ambient or total air temperatures are available.

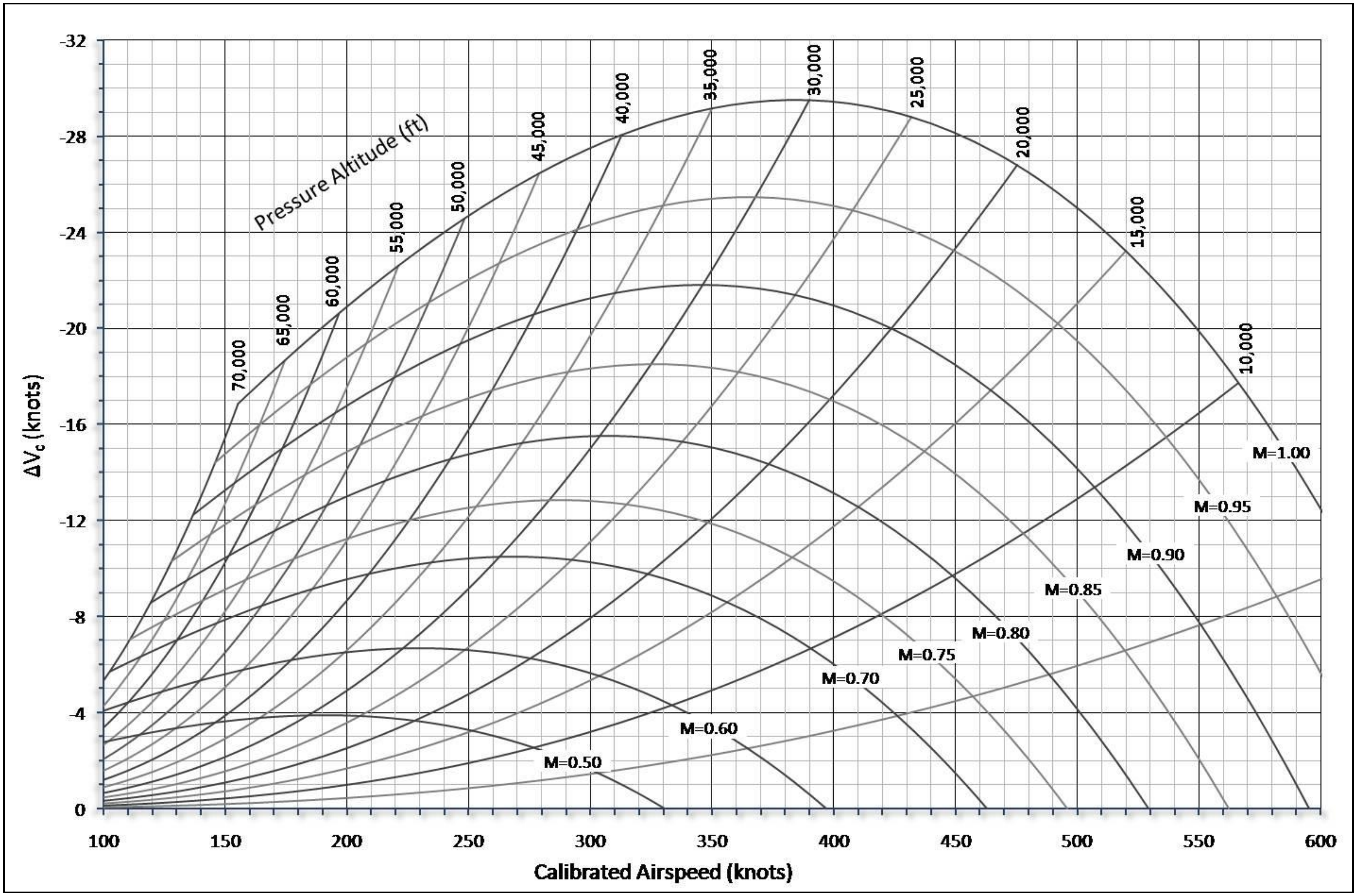

Figure 4 Compressibility Correction for Airspeed, ΔV_c

TRUE AIRSPEED USING P_T, P_A, AND T_T

Most modern flight test aircraft now record some or all of the following parameters:

1. Pressure altitude from an air data computer.
2. Calibrated airspeed from an air data computer.
3. Mach number from an air data computer.
4. Static and/or ambient air pressure.
5. Total and/or differential pressure.
6. Indicated total air temperature.
7. Total air temperature.
8. Ambient air temperature.

The remainder of this handbook will show how to determine one of pressure altitude, calibrated airspeed, or Mach number given the other two or given two of the following three: total air pressure, ambient air pressure, and differential pressure.

1. Pressure altitude is solely a function of ambient air pressure and vice versa. These relationships are a function of the segment of the atmosphere but are valid for both subsonic and supersonic speeds. (See equations 33, 34, 45, and 46.)

2. Calibrated airspeed (subsonic or supersonic) is solely a function of differential pressure, q_c, as seen in equation 62.

$$q_c = P_T - P_a \qquad (62)$$

3. Subsonic and supersonic Mach numbers may be expressed solely as a function of the ratio of P_T and P_a, P_T/P_a, or as a function of q_c/P_a.

CALCULATING AMBIENT AIR TEMPERATURE

Indicated total air temperature is normally the temperature parameter recorded on flight test aircraft. It can be converted to actual total air temperature and to ambient air temperature, equations 84, 85, and 86.

$$T_{Tic} = T_a\,(1+0.2K_RM^2) \qquad (84)$$

$$T_a = T_{Tic} / (1+0.2\,K_RM^2) \qquad (85)$$

$$T_T = T_a\,(1+0.2M^2) \qquad (86)$$

Equating this equation for ambient air temperature with the one in equation 85 produces equations 87 and 88.

$$T_a = T_T/(1+0.2M^2) \tag{87}$$

$$T_T/(1 + 0.2M^2) = T_{T_{ic}}/(1 + 0.2K_R M^2) \tag{88}$$

Multiplying both sides by $(1+0.2M^2)$ produces equation 89 for total air temperature as a function of the instrument corrected total air temperature that was measured in flight.

$$T_T = \left[\frac{(1+0.2M^2)}{(1+0.2K_R M^2)}\right] T_{Tic} \tag{89}$$

Where:

T_{Tic}	=	instrument corrected, indicated total air temperature, degrees R or K
T_a	=	ambient air temperature, degrees R or K
K_R	=	total air temperature probe recovery factor, (determined via flight test), non-dimensional
M	=	true freestream Mach number, non-dimensional
T_T	=	total air temperature, degrees R or K

Given $T_{T_{ic}}$, K_R, and Mach number, use equation 85 to solve for the ambient air temperature and equation 89 for the total air temperature.

The total air temperature probe recovery factor typically varies between 0.40 and 1.00, table 12.

Table 12 Total Air Temperature Probe Recovery Factor

Probe	Typical Recovery Factor Range (n/d)
Flight test quality probe	0.99 to 1.00
‘Good’ production probe	0.95 to 1.00
Average military or production probe for a high performance aircraft	0.90 to 0.99
Typical general aviation production probe	0.40 to 0.90

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

CALCULATING TRUE AIRSPEED

Mach number, by definition, is equal to true airspeed divided by the local speed of sound. Therefore:

$$M = \frac{V_T}{a} \tag{73}$$

$$V_T = M \cdot a \tag{90}$$

Recalling equations 60 and 74:

$$\boxed{M = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{60}$$

$$a = (\gamma RT)^{0.5} \tag{74}$$

Substituting equations 60 and 74 into equation 90 produces equations 91 through 95.

$$V_T = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} (\gamma^{RT})^{0.5} \tag{91}$$

$$V_T = \left\{5\gamma^{RT}\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} \tag{92}$$

$$P = \rho RT \tag{4}$$

$$RT = \frac{P}{\rho} \tag{93}$$

$$\gamma = 1.4$$

$$V_T = \left\{5(1.4)\left(\frac{P_a}{\rho_a}\right)\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} \tag{94}$$

$$\boxed{V_T = \left\{7\left(\frac{P_a}{\rho_a}\right)\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{95}$$

Equation 95 represents one equation with three unknowns: P_T, P_a, and ρ_a.

Rearranging equation 81 and substituting ($q_c + P_a$) for P_T results in equations 96 and 97.

$$V_T = \left(7\left(\frac{P_a}{\rho_a}\right)\left\{\left[\frac{(q_c+P_a)}{P_a}\right]^{1/3.5} -1\right\}\right)^{0.5} \tag{96}$$

$$V_T = \left(7\left(\frac{P_a}{\rho_a}\right)\left\{\left[\left(\frac{q_c}{P_a}\right) +1\right]^{1/3.5} -1\right\}\right)^{0.5} \tag{97}$$

The total air pressure, P_T, has been removed; however, equation 97 still has three unknowns: q_c, P_a, and ρ. Equation 97 is the classic form of the equation for true airspeed.

Going back to equation 90 and starting over produces equations 98 through 106.

$$V_T = M \cdot a \tag{90}$$

$$V_T = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} (\gamma RT)^{0.5} \tag{91}$$

$$a = (\gamma RT)^{0.5} \tag{74}$$

$$V_T = a\left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} \tag{98}$$

$$a_{SL} = (\gamma RT_{SL})^{0.5} \tag{75}$$

$$\frac{a}{a_{SL}} = \left(\frac{\gamma RT}{\gamma RT_{SL}}\right)^{0.5} = (T_a/T_{SL})^{0.5} = \theta^{0.5} \tag{76}$$

$$a = a_{SL}\theta^{0.5} \tag{79}$$

$$V_T = a_{SL}\,\theta^{0.5}\left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5} \tag{99}$$

$$\boxed{V_T = a_{SL}\left\{5\,\theta\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{100}$$

$$\left(\frac{P_T}{P_a}\right) = \left(\frac{q_c + P_a}{P_a}\right) = \left(\frac{q_c}{P_a}\right) + 1 \tag{101}$$

$$\boxed{V_T = a_{SL}\left(5\,\theta\left\{\left[\left(\frac{q_c}{P_a}\right) + 1\right]^{1/3.5} - 1\right\}\right)^{0.5}} \tag{102}$$

$$\frac{T_a}{T_{SL}} = \theta \tag{103}$$

$$V_T = a_{SL}\left(\frac{5}{T_{SL}}\right)^{0.5}\left\{\left[\left(\frac{q_c}{P_a}\right) + 1\right]^{1/3.5} - 1\right\}^{0.5}(T_a)^{0.5} \tag{104}$$

$$M = \frac{V_T}{a} \tag{73}$$

$$a = a_{SL}\theta^{0.5} \tag{79}$$

$$M = \frac{V_T}{(a_{SL}\theta^{0.5})} \tag{105}$$

Or

$$\boxed{V_T = a_{SL}M\theta^{0.5}} \tag{106}$$

Equations 91, 92, 94 through 100, 102, 104, and 106 are all valid equations for true airspeed. Unfortunately, they all represent one equation with three unknowns. Faced with this dilemma, these equations have historically been simplified by introducing equivalent and calibrated airspeeds.

EQUIVALENT AIRSPEED

Equivalent airspeed is not normally used with jet-powered aircraft except by structures engineers. It is used for piston-powered, propeller-driven aircraft and for turboprop-powered aircraft. For the special case of sea level on a standard day; equivalent airspeed, calibrated airspeed, and true airspeed are numerical equal. Equivalent airspeed is always less than either calibrated airspeed or true airspeed for density altitudes above sea level.

Classically, equivalent airspeed has been developed from equation 97.

$$\boxed{V_T = \left(7\left(\frac{P_a}{\rho_a}\right)\left\{\left[\left(\frac{q_c}{P_a}\right)+1\right]^{1/3.5} -1\right\}\right)^{0.5}} \tag{97}$$

The ambient air density in equation 97 is replaced by the sea level standard day value, ρ_{SL}, producing equation 107.

$$\boxed{V_e = \left(7\left(\frac{P_a}{\rho_{SL}}\right)\left\{\left[\left(\frac{q_c}{P_a}\right)+1\right]^{1/3.5} -1\right\}\right)^{0.5}} \tag{107}$$

Equation 107 has two unknowns, P_a and q_c. Comparing equations 97 and 107 results in the following relationship, equations 108 through 110.

$$V_e = V_T \cdot \sigma^{0.5} \tag{108}$$

Where:

$$\sigma = \frac{\rho}{\rho_{SL}} \tag{109}$$

Or more typically,

$$V_T = \frac{V_e}{\sqrt{\sigma}} \tag{110}$$

A more usable equation relating equivalent airspeed, Mach number, and ambient air pressure ratio will be derived in the next section.

INCOMPRESSIBLE DYNAMIC PRESSURE

The two classic equations for incompressible dynamic pressure are equations 111 and 112.

$$\bar{q} = \tfrac{1}{2}\,\rho\, V_T^{\,2} \tag{111}$$

And

$$\bar{q} = \tfrac{1}{2}\,\rho_{SL}\, V_e^{\,2} \tag{112}$$

Note, you may solve the two equations for a relationship between V_e and V_T, as given in equations 113 through 115:

$$\bar{q} = \tfrac{1}{2}\,\rho V_T^{\,2} = \tfrac{1}{2}\rho_{SL} V_e^{\,2} \tag{113}$$

$$\rho V_T^{\,2} = \rho_{SL}\, V_e^{\,2} \tag{114}$$

$$V_T^{\,2} = V_e^{\,2}/\left(\frac{\rho}{\rho_{SL}}\right) \tag{115}$$

$$\sigma = \frac{\rho}{\rho_{SL}} \tag{109}$$

$$V_T = \frac{V_e}{\sqrt{\sigma}} \tag{110}$$

A more useful relationship for testing with high performance aircraft is derived from using equations 111, 90, and 74.

$$\bar{q} = \tfrac{1}{2}\,\rho V_T^{\,2} \tag{111}$$

$$V_T = M \cdot a \tag{90}$$

$$a = (\gamma RT)^{\,0.5} \tag{74}$$

Inserting equations 90 and 74 into equation 111 you produce equations 116 through 123.

$$\bar{q} = \tfrac{1}{2}\rho\left[M(\gamma\, RT)^{\,0.5}\right]^{\,2} \tag{116}$$

$$\bar{q} = \tfrac{1}{2}\gamma\rho RTM^2 \tag{117}$$

$$P = \rho RT \tag{4}$$

$$\bar{q} = \tfrac{1}{2}\gamma\, PM^2 \tag{118}$$

$$\delta = \frac{P_a}{P_{SL}} \tag{69}$$

$$P = P_{SL}\,\delta \tag{70}$$

$$\bar{q} = \tfrac{1}{2}\gamma(P_{SL}\delta)M^2 \tag{119}$$

$$\bar{q} = \tfrac{1}{2}\gamma P_{SL}M^2\delta \tag{120}$$

$$\gamma = 1.4$$

$$\bar{q} = \tfrac{1}{2}(1.4)P_{SL}M^2\,\delta \tag{121}$$

$$\bar{q} = 0.7P_{SL}\,M^2\delta \tag{122}$$

For $P_{SL} = (2116.216\ 6)\ (\text{lb/ft}^2)$ and $\bar{q}$ having units of pounds per square foot:

$$\boxed{\bar{q} = (1481.351\ 6)\ M^2\delta} \tag{123}$$

ANOTHER EQUATION FOR EQUIVALENT AIRSPEED

Combining equations 112 and 122 produces equations 129 and 130.

$$\bar{q} = \tfrac{1}{2}\rho_{SL}V_e^2 \qquad (112)$$

$$\bar{q} = 0.7P_{SL}\,M^2\,\delta \qquad (122)$$

Equating the right sides of equations 112 and 122 produces equations 124 through 130.

$$\tfrac{1}{2}\rho_{SL}V_e^2 = 0.7P_{SL}\,M^2\delta \qquad (124)$$

$$V_e^2 = 2(0.7)\left(\frac{P_{SL}}{\rho_{SL}}\right)M^2\,\delta \qquad (125)$$

$$2(0.7) = 1.4 = \gamma$$

$$V_e^2 = \gamma\left(\frac{P_{SL}}{\rho_{SL}}\right)M^2\,\delta \qquad (126)$$

$$P = \rho RT \qquad (4)$$

$$\frac{P}{\rho} = RT \qquad (93)$$

$$V_e^2 = (\gamma RT_{SL})\,M^2\,\delta \qquad (127)$$

$$a_{SL} = (\gamma RT_{SL})^{0.5} \qquad (75)$$

$$V_e^2 = a_{SL}^2 M^2\,\delta \qquad (128)$$

$$\boxed{V_e = a_{SL}\,M\,\delta^{0.5}} \qquad (129)$$

Or,

$$\boxed{M = (V_e/a_{SL})/\delta^{0.5}} \qquad (130)$$

CALIBRATED AIRSPEED

Calibrated airspeed was 'invented' because mechanical airspeed indicators could not solve equation 97.

$$V_T = \left(7\left(\frac{P_a}{\rho_a}\right)\left\{\left[\left(\frac{q_c}{P_a}\right)+1\right]^{1/3.5}-1\right\}\right)^{0.5} \qquad (97)$$

Equation 97 was transformed into an equation with one input and one output by replacing ρ with ρ_{SL} and P_a with P_{SL}. That resulted in an equation that could be solved mechanically by the airspeed indicator, equation 136.

$$V_c = \left(7\left(\frac{P_{SL}}{\rho_{SL}}\right)\left\{\left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5}-1\right\}\right)^{0.5} \qquad (131)$$

Or,

$$P = \rho RT \qquad (4)$$

$$\frac{P}{\rho} = RT \qquad (93)$$

$$\gamma RT = a^2 \qquad (132)$$

$$\gamma\left(\frac{P}{\rho}\right) = a^2 \qquad (133)$$

$$\frac{P}{\rho} = \frac{a^2}{\gamma} \qquad (134)$$

$$\frac{P_{SL}}{\rho_{SL}} = \frac{(a_{SL})^2}{\gamma} \qquad (135)$$

$$\gamma = 1.4$$

$$\frac{7}{\gamma} = \left(\frac{7}{1.4}\right) = 5$$

Substituting equation 135 into equation 131 produces equations 136 through 140.

$$\boxed{V_c = a_{SL}\left(5\left\{\left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5}-1\right\}\right)^{0.5}} \qquad (136)$$

$$V_c^{\,2} = a_{SL}^{\,2}\, 5\left\{\left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5} -1\right\} \qquad (137)$$

$$\frac{V_c^{\,2}}{(a_{SL})^2\, 5} = \left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5} -1 \qquad (138)$$

$$0.2\left(\frac{V_c}{a_{SL}}\right)^2 = \left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5} -1 \qquad (139)$$

$$0.2\left(\frac{V_c}{a_{SL}}\right)^2+1 = \left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5} \qquad (140)$$

Switching the sides of the equation and raising the exponents of both sides by 3.5 produced equations 141 through 143.

$$\left(\frac{q_c}{P_{SL}}\right)+1 = \left[1+0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} \qquad (141)$$

$$\frac{q_c}{P_{SL}} = \left[1+0.2\left(\frac{V_c}{a_{SL}}\right)\right]^{3.5} -1 \qquad (142)$$

$$\boxed{q_c = P_{SL}\left\{\left[1+0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} -1\right\}} \qquad (143)$$

Equations 136 and 143 define the subsonic relationship between calibrated airspeed and differential pressure, P_T-P_a. Notice that it is not a function of the test day ambient air temperature. The speed of sound at sea level on a standard day, a_{SL}, is a constant (independent of the test day ambient air temperature) as is the ambient air pressure at sea level on a standard day, P_{SL}.

Notice the similarity of equation 67 to equation 143.

$$\frac{q_c}{P_a} = (1+0.2\,M^2)^{3.5} -1 \qquad (67)$$

$$\frac{q_c}{P_{SL}} = \left[1+0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} -1 \qquad (143)$$

$$\frac{q_c}{P_a} = \left(\frac{q_c}{P_{SL}}\right)\left(\frac{P_{SL}}{P_a}\right) \qquad (144)$$

$$\frac{P_a}{P_{SL}} = \delta \tag{69}$$

$$\frac{q_c}{P_a} = \left(\frac{q_c}{P_{SL}}\right)/\delta \tag{145}$$

Substituting equation 145 into equation 67 produces equations 146 and 147.

$$\left(\frac{q_c}{P_{SL}}\right)/\ \delta = (1 + 0.2M^2)^{\ 3.5} -1 \tag{146}$$

$$\frac{q_c}{P_{SL}} = \left[(1 + 0.2\ M^2)^{\ 3.5} -1\right] \delta \tag{147}$$

$$\frac{q_c}{P_{SL}} = \left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{\ 3.5} -1 \tag{143}$$

Comparing equations 143 and 147 at sea level, where $\delta = 1$ on a standard day, shows that Mach number is equal to V_c/a_{SL}. Actually, $\delta = 1$ at a point in the atmosphere where an ambient air pressure ratio equivalent to the sea level standard day value exists independent of the test day ambient air temperature.

Equating the right sides of equations 143 and 147 produces equations 148 through 154.

$$\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^{2}\right]^{\ 3.5} -1 = \left[(1 + 0.2\ M^2)^{\ 3.5} -1\right] \delta \tag{148}$$

$$\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{\ 3.5} = \left[(1 + 0.2M^2)^{\ 3.5} -1\right] \delta + 1 \tag{149}$$

$$1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^{2} = \left\{\left[(1 + 0.2M^2)^{\ 3.5} -1\right] \delta + 1\right\}^{\ 1/3.5} \tag{150}$$

$$0.2\left(\frac{V_c}{a_{SL}}\right)^{2} = \left\{\left[(1+0.2M^2)^{\ 3.5} -1\right]\delta + 1\right\}^{1/3.5} -1 \tag{151}$$

$$\left(\frac{V_c}{a_{SL}}\right)^2 = 5\left(\left\{\left[(1 + 0.2\ M^2)^{3.5} -1\right] \delta + 1\right\}^{\ 1/3.5} -1\right) \tag{152}$$

$$V_c^{\ 2} = 5\ (a_{SL})^2\left(\left\{\left[(1 + 0.2\ M^2)^{3.5} -1\right] \delta + 1\right\}^{\ 1/3.5} -1\right) \tag{153}$$

$$V_c = a_{SL}\left[5\left(\left\{\left[(1 + 0.2\,M^2)^{3.5} - 1\right]\delta + 1\right\}^{1/3.5} - 1\right)\right]^{0.5} \tag{154}$$

Note the equation 154 allows you to directly calculate calibrated airspeed as a function of Mach number and the ambient air pressure ratio.

A similar relationship for Mach number as a function of calibrated airspeed and the ambient air pressure ratio can be derived from equation 148.

$$\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1 = \left[(1 + 0.2\,M^2)^{3.5} - 1\right]\delta \tag{148}$$

Switching the right and left sides and dividing by δ produces equations 155 through 159.

$$(1 + 0.2M^2)^{3.5} - 1 = \left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} \tag{155}$$

$$(1 + 0.2M^2) = \left(\left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} + 1\right)^{1/3.5} \tag{156}$$

$$M^2 = 5\left[\left(\left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} + 1\right)^{1/3.5} - 1\right] \tag{157}$$

$$M = \left\{5\left[\left(\left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} + 1\right)^{1/3.5} - 1\right]\right\}^{0.5} \tag{158}$$

The ambient air pressure ratio and therefore pressure altitude can also be determined from equation 148.

$$\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1 = \left[(1 + 0.2\,M^2)^{3.5} - 1\right]\delta \tag{148}$$

$$\delta = \left\{\frac{\left[1+0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1}{[1+0.2M^2\,]^{3.5} - 1}\right\} \tag{159}$$

Notice that equations 136 and 154 allow you to calculate calibrated airspeed without knowing ambient or total air temperature. Equation 136 only requires differential pressure and equation 154 only requires Mach number and the ambient air pressure ratio.

SAMPLE PROBLEMS

These sample problems were selected to show the proper use of the equations presented earlier. The references to 'below 36,000 feet' and 'above 36,000 feet' are references to the discontinuity in the ambient air temperature model that occurs at 11,000 geopotential meters, approximately 36,089 geopotential feet. That value has been 'rounded off' in the section titles to 36,000 feet to simplify the section titles.

CALCULATE MACH NUMBER GIVEN PRESSURE ALTITUDE (BELOW 36,000 FEET) AND CALIBRATED AIRSPEED

Given:

$$H_p = 30{,}000 \text{ (feet)}$$

$$V_c = 200 \text{ (KCAS)}$$

<u>First Approach:</u>

1. Calculate δ using equation 33.
2. Calculate ambient pressure using equation 70.
3. Calculate differential pressure using equation 143.
4. Calculate total air pressure using equation 63.
5. Calculate $\frac{P_T}{P_a}$
6. Calculate Mach number using equation 60.

$$\boxed{\delta = \{1 - (6.875\,585\,7 \times 10^{-6})\,[H_p\,(ft)]\}^{5.255\,880}} \qquad (33)$$

$$\delta = 0.296\,961$$

$$P_a = P_{SL}\,\delta \qquad (70)$$

$$P_{SL} = 29.921\,252 \text{ (in Hg)}$$

$$P_a = 8.885\,445 \text{ (in Hg)}$$

$$q_c = P_{SL}\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} \qquad (143)$$

$$a_{SL} = 661.478\,6 \text{ (knots)}$$

Then:

$$q_c = 1.958\,885 \text{ (in Hg)}$$

$$\boxed{P_T = P_a + q_c} \qquad (63)$$

$$P_T = 10.844\ 330 \text{ (in Hg)}$$

$$\frac{P_T}{P_a} = 1.220\ 460$$

$$\boxed{M = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \qquad (60)$$

$$M = 0.5412$$

Second Approach:

Use equation 158:

$$\boxed{M = \left\{5\left[\left(\left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} + 1\right)^{1/3.5} - 1\right]\right\}^{0.5}} \qquad (158)$$

From above:

δ = 0.296 961

V_c = 200 (KCAS)

a_{SL} = 661.4786 (knots)

M = 0.5412

Although the answers for Mach numbers are only shown to four significant figures, both approaches give the same answer to at least six significant figures.

CALCULATE MACH NUMBER GIVEN PRESSURE ALTITUDE (ABOVE 36,000 FEET) AND CALIBRATED AIRSPEED

Given:

H_p = 60,000 (feet)

V_c = 100 (KCAS)

First Approach:

1. Calculate δ using equation 45.
2. Calculate ambient air pressure using equation 70.

3. Calculate differential pressure using equation 143.
4. Calculate total air pressure using equation 63.
5. Calculate $\frac{P_T}{P_a}$.
6. Calculate Mach number using equation 60.

$$\boxed{\delta = (0.223\,360\,9)\ e^{-([(4.806\,346\,1) \times 10^{-5}]\{[H(ft)]-36{,}089.239\})}} \tag{45}$$

$$\delta = 0.070\,778\,5$$

$$P_a = P_{SL}\ \delta \tag{70}$$

$$P_{SL} = 29.921\,252 \text{ (in Hg)}$$

$$P_a = 2.117\,780 \text{ (in Hg)}$$

$$\boxed{q_c = P_{SL}\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\}} \tag{143}$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

Then:

$$q_c = 0.481\,422 \text{ (in Hg)}$$

$$P_T = P_a + q_c \tag{63}$$

$$P_T = 2.599\,202\,6 \text{ (in Hg)}$$

$$\frac{P_T}{P_a} = 1.227\,324$$

$$\boxed{M = \left\{5\left[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{60}$$

$$M = 0.5489$$

Second Approach:

Use equation 158:

$$\boxed{M = \left\{5\left[\left(\left(\frac{1}{\delta}\right)\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\} + 1\right)^{1/3.5} - 1\right]\right\}^{0.5}} \tag{158}$$

From above:

$$\delta = 0.070\ 778\ 5$$

$$V_c = 100 \text{ (KCAS)}$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

$$M = 0.5489$$

Both approaches gave the same answer through six significant figures.

CALCULATE CALIBRATED AIRSPEED GIVEN PRESSURE ALTITUDE (BELOW 36,000 FEET) AND MACH NUMBER (TOWER FLYBY EXAMPLE)

Given:

$$H_p = 2{,}500 \text{ (feet)}$$

$$M = 1.000$$

$$P_{SL} = 29.921\ 252 \text{ (in Hg)}$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

<u>First Approach:</u>

1. Calculate δ using equation 33.
2. Calculate ambient air pressure using equation 70.
3. Calculate P_T/P_a using equation 56.
4. Calculate $P_{T.}$
5. Calculate differential pressure, q_c, using equation 54.
6. Calculate calibrated airspeed using equation 126.

$$\boxed{\delta = \{1 - (6.875\ 585\ 7 \text{ x } 10^{-6})\ [H_p \text{ (ft)}]\}^{5.255\ 880}} \qquad (33)$$

$$\delta = 0.912\ 900\ 3$$

$$P_a = P_{SL}\delta \qquad (70)$$

$$P_a = 27.315\ 120 \text{ (in Hg)}$$

$$\boxed{\frac{P_T}{P_a} = (1 + 0.2\ M^2)^{3.5}} \qquad (56)$$

For Mach number = 1:

$$\frac{P_T}{P_a} = 1.892\,929\,159$$

$$P_T = (1.892\,929\,159)(27.315\,120)(\text{in Hg})$$

$$P_T = 51.705\,587\ (\text{in Hg})$$

$$q_c = P_T - P_a \tag{62}$$

$$q_c = [(51.705\,587) - (27.315\,120)](\text{in Hg})$$

$$q_c = 24.390\,467\ (\text{in Hg})$$

Using units of pounds per square foot, this value of q_c is 1725.045. The value of q_c for 661.479 KCAS, the speed of sound at sea level on a standard day, is 1,819.631 6 pounds per square foot.

$$\boxed{V_c = a_{SL} \left(5\left\{\left[\left(\frac{q_c}{P_{SL}}\right) +1\right]^{1/3.5} -1\right\}\right)^{0.5}} \tag{136}$$

$$V_c = 637.395\ (\text{KCAS})$$

<u>Second Approach:</u>

Use equation 154.

$$\boxed{V_c = a_{SL} \left[5 \left(\{[(1 + 0.2\ M^2)^{3.5} -1]\ \delta + 1\}^{1/3.5} -1\right)\right]^{0.5}} \tag{154}$$

From above:

$$M = 1.000$$

$$a_{SL} = 661.4786\ (\text{knots})$$

$$\delta = 0.912\,900\,3$$

$$V_c = 637.395\ (\text{KCAS})$$

The two approaches gave the same answer to eight significant figures.

CALCULATE CALIBRATED AIRSPEED GIVEN PRESSURE ALTITUDE (BELOW 36,000 FEET) AND MACH NUMBER

Given:

$$H_p = 20{,}000 \text{ (feet)}$$

$$M = 0.800$$

$$P_{SL} = 29.921\,252 \text{ (in Hg)}$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

First Approach:

1. Calculate δ using equation 33.
2. Calculate ambient air pressure using equation 70.
3. Calculate P_T/P_a using equation 56.
4. Calculate P_T.
5. Calculate differential pressure, q_c, using equation 62.
6. Calculate calibrated airspeed using equation 136.

$$\boxed{\delta = \{1 - (6.875\,585\,7 \times 10^{-6})\,[H_p\,(\text{ft})]\}^{5.255\,880}} \quad (33)$$

$$\delta = 0.459\,543$$

$$P_a = P_{SL}\,\delta \quad (70)$$

$$P_a = 13.750\,115 \text{ (in Hg)}$$

$$\boxed{\frac{P_T}{P_a} = (1 + 0.2\,M^2)^{3.5}} \quad (56)$$

$$\frac{P_T}{P_a} = 1.524\,340$$

$$P_T = 20.959\,850 \text{ (in Hg)}$$

$$q_c = P_T - P_a \quad (62)$$

$$q_c = 7.209\,735 \text{ (in Hg)}$$

$$V_c = a_{SL} \left(5\left\{\left[\left(\frac{q_c}{P_{SL}}\right)+1\right]^{1/3.5} -1\right\}\right)^{0.5} \tag{136}$$

V_c = 373.084 (KCAS)

Second Approach:

Use equation 154.

$$V_c = a_{SL} \left[5 \left(\left\{\left[(1 + 0.2\, M^2)^{3.5} -1\right] \delta + 1\right\}^{1/3.5} -1\right)\right]^{0.5} \tag{154}$$

From above:

M = 0.800

a_{SL} = 661.4786 (knots)

δ = 0.459 543

V_c = 373.084 (KCAS)

The two approaches gave the same result to six significant figures.

CALCULATE CALIBRATED AIRSPEED GIVEN PRESSURE ALTITUDE (ABOVE 36,000 FEET) AND MACH NUMBER

Given:

H_p = 50,000 (feet)

M = 0.950

P_{SL} = 29.291 252 (in Hg)

a_{SL} = 661.4786 (knots)

First Approach.

1. Calculate δ using equation 45.
2. Calculate ambient air pressure using equation 70.
3. Calculate P_T/P_a using equation 56.
4. Calculate $P_{T.}$
5. Calculate differential pressure, q_c, using equation 62.
6. Calculate calibrated airspeed using equation 136.

$$\boxed{\delta = (0.223\ 360\ 9)e^{-([(4.806\ 346\ 1)\ x\ 10^{-5}]\{[H(ft)]-36{,}089.239\})}} \quad (45)$$

$$\delta = 0.114\ 455\ 9$$

$$P_a = P_{SL}\delta \quad (70)$$

$$P_a = 3.424\ 663\ \text{(in Hg)}$$

$$\boxed{\left(\frac{P_T}{P_a}\right) = (1 + 0.2\ M^2)^{3.5}} \quad (56)$$

$$\frac{P_T}{P_a} = 1.787\ 438$$

$$P_T = 6.121\ 373\ \text{(in Hg)}$$

$$q_c = P_T - P_a \quad (62)$$

$$q_c = 2.696\ 710\ \text{(in Hg)}$$

$$\boxed{V_c = a_{SL}\left(5\left\{\left[\frac{q_c}{P_{SL}} + 1\right]^{1/3.5} - 1\right\}\right)^{0.5}} \quad (136)$$

$$V_c = 233.690\ \text{(KCAS)}$$

<u>Second Approach:</u>

Use equation 154.

$$\boxed{V_c = a_{SL}\left[5\left(\{[(1 + 0.2\ M^2)^{3.5} - 1]\ \delta + 1\}^{1/3.5} - 1\right)\right]^{0.5}} \quad (154)$$

From above:

$$M = 0.95$$

$$a_{SL} = 661.4786\ \text{(knots)}$$

$$\delta = 0.114\ 455\ 9$$

$$V_c = 233.690\ \text{(KCAS)}$$

The two results matched to nine significant figures.

CALCULATE PRESSURE ALTITUDE GIVEN CALIBRATED AIRSPEED AND MACH NUMBER

Given:

$$V_c = 350 \text{ (KCAS)}$$

$$M = 0.900$$

$$P_{SL} = 29.921\ 252 \text{ (in Hg)}$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

First Approach:

1. Calculate differential pressure, q_c, using equation 143.
2. Calculate $\frac{P_T}{P_a}$ using equation 56.
3. Calculate q_c as a function of P_a, using equation 62.
4. Calculate P_a.
5. Calculate the ambient air pressure ratio, δ.
6. Calculate the pressure altitude using equation 34.

$$\boxed{q_c = P_{SL}\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2\right]^{3.5} - 1\right\}} \quad (143)$$

$$q_c = 6.285\ 831 \text{ (in Hg)}$$

$$\boxed{\left(\frac{P_T}{P_a}\right) = (1 + 0.2\ M^2)^{3.5}} \quad (56)$$

$$\frac{P_T}{P_a} = 1.691\ 303$$

$$P_T = (1.691\ 303)\ P_a$$

$$q_c = P_T - P_a \quad (62)$$

$$q_c = (1.691\ 303)\ P_a - P_a$$

$$q_c = (0.691\ 303)\ P_a = 6.285\ 831$$

$$Pa = (6.285\ 831)/(0.691\ 303)$$

$$P_a = 9.092\ 728 \text{ (in Hg)}$$

$$\boxed{[Hp\ (ft)] = 145{,}442.16\ (1 - \delta^{0.190\ 263\ 1})} \tag{34}$$

$$H_p = 29{,}492.36 \text{ (feet)}$$

Second Approach:

Use equation 159 to solve for δ.

$$\boxed{\delta = \left\{ \frac{\left[\left(1+0.2\left(\frac{V_c}{a_{SL}}\right)^2\right)^{3.5} - 1\right]}{\left[(1+0.2M^2)^{3.5}-1\right]} \right\}} \tag{159}$$

Given:

$$V_c = 350 \text{ (KCAS)}$$

$$M = 0.900$$

$$a_{SL} = 661.4786 \text{ (knots)}$$

$$\delta = 0.303\ 889$$

Delta is greater than 0.223 361, therefore the pressure altitude is below 36,000 feet.

$$\boxed{[Hp\ (ft)] = 145{,}442.16\ (1 - \delta^{0.190\ 263\ 1})} \tag{34}$$

$$H_p = 29{,}492.36 \text{ (feet)}$$

The two approaches gave the same answer to eight significant figures.

SUMMARY

Equations were derived which were consistent with the tables documenting the lowest two segments of the 1976 U.S. standard atmosphere and the 1993 ICAO international standard atmosphere. These equations related ambient air pressure and pressure altitude in the troposphere and in the stratosphere. Equations were also derived for subsonic Mach number, calibrated airspeed, equivalent airspeed, differential pressure, and incompressible dynamic pressure. (Supersonic relationships are presented in appendix B.)

Relationships of ambient air pressure and total air pressure with pressure altitude, calibrated airspeed, equivalent airspeed, and Mach number were developed, which did not require a knowledge of either ambient air temperature or total air temperature. Given two values for pressure altitude, Mach number, and calibrated airspeed, the third could be calculated.

Ambient air temperature or total air temperature were only required if one wanted to calculate either true airspeed or the local speed of sound. All others could be determined as functions of only ambient and total air pressures.

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APPENDIX A - UNITS CONVERSIONS

SOURCE MATERIAL

Most of the information for this appendix came from two National Institute of Standards and Technology (NIST) publications. First, NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*, reference 13. Second, NIST Special Publication 330, *The International System of Units (SI)*, reference 25.

LENGTH

Since 1983 the meter has been defined as the distance travelled by light in a vacuum during a time interval of 1/(299,792,458)th of a second. The previous definition (from 1960 until 1983) was based on the wavelength of krypton 86 radiation. Between 1889 and 1960, the length of a meter was defined by the platinum bar stored in Paris, France. The earliest definition (1791) of a meter was based on a fraction $(1/(10^7)^{th}$ of the distance along the curvature of a line of longitude passing through Paris between the equator and the North Pole. The following have been accepted as exact by international agreements:

1. One international foot is exactly equal to 0.3048 meter.

2. One nautical mile is exactly equal to 1,852 meters.

Table A1 presents some units conversions for length.

Table A1 Length Conversions

To Convert		
From	To	Multiply By
foot	meter	0.3048 (exact)
meter	foot	(1/0.3048) = 3.280 839 895
nautical mile	meter	1,852 (exact)
meter	nautical mile	(1/1,852) = (5.399 568) x 10^{-4}
foot	nautical mile	(1/6076.115) = (1.645 788) x 10^{-4}
nautical mile	foot	6,076.115 486
statute mile	foot	5,280 (exact)
statute mile	meter	(5,280 x 0.304 8) = 1,609.344

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

TEMPERATURE

$$T(\text{deg F}) = \{[T(\text{deg C})] \times 1.8\} + 32 \tag{A1}$$

$$T(\text{deg C}) = \{[T(\text{deg F})] - 32\} / 1.8 \tag{A2}$$

$$T(\text{deg R}) = [T(\text{deg F})] + 459.67 \tag{A3}$$

$$T(K) = [T(\text{deg C})] + 273.15 \tag{A4}$$

Note: The absolute temperature (K) or kelvin is no longer referred to as degrees K.

TIME

The accepted definition of a second since 1968 has been:

"The second is the duration of 9,192, 631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."

In 1997, the definition was further defined by adding the sentence, "This definition refers to a cesium atom at rest at a temperature of 0K". The second use to be defined as 1/86,400 of a mean solar day or 60 seconds per minute times 60 minutes per hour times 24 hours per day.

SPEED

Table A2 Speed or Velocity Conversions

To Convert		Multiply By
From	To	
ft/sec	m/sec	0.3048 (exact)
m/sec	ft/sec	3.280 839 895
nm/hr	m/sec	(1,852/3,600) = 0.514 444
m/sec	nm/hr	1.943 844 492
ft/sec	nm/hr	0.592 483 801
nm/hr	ft/sec	1.687 809 857

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

MASS AND WEIGHT

METRIC SYSTEM

In the metric system there is a clear distinction between mass and weight. Mass has units of kilograms (or grams) while weight has units of $kg \cdot m/(sec)^2$ or newtons (N). A newton is the force required to accelerate a 1 kilogram mass by 1 meter per second squared.

$$F = m \cdot a \qquad (A5)$$

$$kg \cdot m/(sec)^2 = kg \cdot [m/(sec)^2]$$

Until 1889, a kilogram was the mass of a cubic decimeter of water. After 1889 a kilogram became the mass of "the international prototype of the kilogram" made from platinum and stored in Paris, France.

U.S. CUSTOMARY UNITS

The U.S. customary units are unclear at best with regard to the differences between mass and weight units. Some of the units that have been used for one or both include:

1. pounds
2. pounds mass

3. pounds force
4. pound weight
5. poundals
6. slugs

Most of the confusion comes from using mass and weight interchangeably. If you weigh an aircraft and its ‘weight’ is 100,000 pounds force with a local gravity of 32.170 feet per second squared, the mass of the aircraft would be 100,000 (pounds force) divided by 32.170 (ft/sec^2) or 3,108.846 167 ($lb_f \cdot sec^2/ft$). If you then multiply that mass by the reference value for the acceleration of gravity, 32.17405 (ft/sec^2), then the ‘weight’ of the aircraft would be 100,012.6 pounds. The difference between the two ‘weights’ in this example is less than 13 pounds in 100,000, less than 0.013 percent. If we had assumed that the local acceleration due to gravity was equal to the reference value, then the two weights would have been identical.

In general, ‘pounds’ is not definitively either a unit of mass or weight. Pounds mass and slugs are units of mass. Pounds force, pounds weight, and poundals are units of force or weight. Table A3 summarizes these different units.

Table A3 Units of Mass and Force in the U.S. Customary Units

Force	Mass	Acceleration (ft/sec^2)
1 pound	1 pound	32.17405
1 pound force	1 pound mass	32.17405
1 pound weight	1 pound mass	32.17405
1 poundal	1 pound mass	1.0
32.17405 poundals	1 pound mass	32.17405
1 pound force	1 slug	1.0
32.17405 pound force	1 slug	32.17405

Notes:
1. (Force) = (mass) x (acceleration)
2. The pounds or pounds mass in the first three rows must be divided by 32.17405 ft/sec^2, a ‘units conversion.’
3. Abbreviations, acronyms, and symbols are defined in appendix H.

The following comments are introduced to try to clarify some of the confusion presented in table A3:

1. One pound force can accelerate 1 pound mass 32.17405 (ft/sec^2).
2. One pound weight is just another name for 1 pound force.
3. One pound force can accelerate 1 slug of mass 1 (ft/sec^2). Therefore, 32.17405 pounds mass are equivalent to 1 slug.
4. One poundal can accelerate 1 pound mass 1 (ft/sec^2). Therefore, 32.17405 poundals are equivalent to 1 pound force.
5. Table A3 contains both consistent and nonconsistent sets of units.

Consistent Units:

One pound force can accelerate 1 slug of mass 1 (ft/sec^2), equation A5.

$$F = m \cdot a \tag{A5}$$

$$1\,(lb_f) = 1(\text{slug})\;1(\text{ft/sec}^2)$$

$$\text{slug} = lb_f \cdot \text{sec}^2/\text{ft}$$

One poundal can accelerate 1 pound mass 1 (ft/sec^2).

$$F = m \cdot a \tag{A5}$$

$$1(\text{poundal}) = 1(lb_m)\;1(\text{ft/sec}^2)$$

$$(lb_m) = (\text{poundal}) \cdot \text{sec}^2/\text{ft}$$

Nonconsistent Units:

One pound force can accelerate 1 pound mass 32.17405 (ft/sec^2).

$$F = m \cdot a \tag{A5}$$

$$1(lb_f) = 1(lb_m) \cdot [32.17405\;(\text{ft/sec}^2)]$$

$$1 \neq 32.17405$$

A 'gravitational conversion factor', g_c, is introduced.

$$g_c = 32.17405 \left(\frac{lb_m}{lb_f}\right)\left(\frac{ft}{sec^2}\right) \tag{A6}$$

$$F = \left(\frac{1}{g_c}\right) \cdot m \cdot a \tag{A7}$$

Now:

$$1(\mathrm{lb_f}) \quad = \quad \left[\left(\frac{1}{32.17405}\right)\left(\frac{\mathrm{lb_f}}{\mathrm{lb_m}}\right)\left(\frac{\mathrm{sec}^2}{\mathrm{ft}}\right)\right] \cdot [1\,(1\mathrm{b_m})]\,[32.17405\,(\mathrm{ft/sec}^2)]$$

$$1(\mathrm{lb_f}) \quad = \quad 1(\mathrm{lb_f})$$

The units in the equation F = $(1/g_c) \cdot m \cdot a$ are now compatible.

<u>Units Conversions:</u>

Units conversions for mass, weight, and force between the SI system and the U.S. customary units in table A4 were extracted from appendix B of reference 13.

Table A4 Mass, Weight, and Force Units Conversions

To Convert		Multiply By
From	To	
pound force	newton	4.448 222
pound mass	kilogram	0.453 592 37
poundal	newton	0.138 255 0
slug	kilogram	14.593 90
newton	pound force	0.224 808 9
kilogram	pound mass	2.204 622 6
newton	poundal	7.233 011 5
kilogram	slug	0.068 521 78

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

PRESSURE

Table A5 presents units conversions for ambient air pressure.

Table A5 Ambient Air Pressure Units Conversions

<table>
<tr><th colspan="2">To Convert</th><th rowspan="2">Multiply By</th></tr>
<tr><th>From</th><th>To</th></tr>
<tr><td>pounds per square inch</td><td rowspan="8">pascal or (N/m²)</td><td>6,894.757</td></tr>
<tr><td>pounds per square foot</td><td>47.880 257</td></tr>
<tr><td>millimeters of mercury (Torr)</td><td>133.322 368 4</td></tr>
<tr><td>inches of mercury</td><td>3,386.389</td></tr>
<tr><td>bar</td><td>100,000 (exact)</td></tr>
<tr><td>millibar (mb) or hectopascals (hP_a)</td><td>100 (exact)</td></tr>
<tr><td>kilopascal</td><td>1,000 (exact)</td></tr>
<tr><td>atmosphere</td><td>101,325.0 (exact)</td></tr>
<tr><td>pascal</td><td>N/m^2</td><td>1.00 (exact)</td></tr>
<tr><td>pound per square foot</td><td>inches of mercury</td><td>0.014 139 03</td></tr>
</table>

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

Table A5 Ambient Air Pressure Units Conversions (Concluded)

To Convert		
From	To	Multiply By
pound per square foot	millibars	0.478 802 57
inch of mercury	pounds per square foot	70.726 207 6
inch of mercury	millibars	33.863 89
millibars	pounds per square foot	2.088 543 51
millibars	inches of mercury	0.029 529 98
atmosphere	inches of mercury	29.921 252 4

Note: Abbreviations, acronyms, and symbols are defined in appendix H.

APPENDIX B - SUPERSONIC RELATIONSHIPS

INTRODUCTION

The body of this handbook was developed for subsonic flight in either the troposphere or the stratosphere. This appendix provides a brief introduction into supersonic flight. The scope of this appendix will be limited to determining the equations required to determine Mach number and calibrated airspeed behind a normal shock. The following assumptions will be made:

1. The supersonic Mach number is low enough that the ratio of specific heats, γ, may still be assumed to be exactly equal to 1.400. (This will restrict the validity of these equations to Mach numbers less than something between 2.0 and 3.0.) The exact limit is not defined.

2. The gas dynamics equation for the change in total pressure across a normal shock will be assumed to be valid immediately behind the shock.

3. The gas dynamics equation for the change in static pressure across a normal shock will be assumed to be valid immediately behind the shock. However, it will be assumed that the loss in static pressure behind the normal shock will be regained prior to reaching the static ports. The NATO *Flight Test Manual*, reference 26, states that the flush static ports should be more than 8 to 10 pitot tube diameters behind the pitot opening to allow for this static pressure recovery to occur.

NORMAL SHOCK RELATIONSHIPS

The following equations (B1 through B10) from gas dynamics for normal shocks are assumed to be valid.

STATIC PRESSURE

$$\frac{P_2}{P_1} = \frac{[2\gamma M_1{}^2 - (\gamma - 1)]}{(\gamma + 1)} \tag{B1}$$

where:

P_1	=	static pressure ahead of the normal shock, freestream ambient air pressure
P_2	=	static pressure immediately behind the normal shock (not at the static ports)
M_1	=	Mach number ahead of the normal shock, freestream Mach number
γ	=	exactly 1.400 (assumed)

MACH NUMBER

$$M_2{}^2 = \frac{M_1{}^2 + \left(\frac{2}{\gamma - 1}\right)}{\left\{\left[\frac{2\gamma}{(\gamma - 1)}\right] M_1{}^2 - 1\right\}} \tag{B2}$$

An alternative form of equation B2 is created by multiplying the right side of the equation by $(\gamma - 1)/(\gamma - 1)$, equations B3 and B4.

$$M_2{}^2 \quad = \quad \frac{(\gamma-1)M_1{}^2 + 2}{\left[2\gamma M_1{}^2 - (\gamma-1)\right]} \qquad \text{(B3)}$$

TOTAL PRESSURE BEHIND THE SHOCK

$$\frac{P_{T_2}}{P_2} \quad = \quad \left\{1 + \left[\frac{(\gamma-1)}{2}\right] M_2{}^2\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]} \qquad \text{(B4)}$$

(Q_C/P_A) AS A FUNCTION OF THE FREESTREAM SUPERSONIC MACH NUMBER

Combining equations B4 and B1:

$$\left(\frac{P_{T_2}}{P_2}\right)\left(\frac{P_2}{P_1}\right) \quad = \quad \left[\frac{2\gamma M_1{}^2 - (\gamma-1)}{(\gamma+1)}\right]\left\{1 + \left[\frac{(\gamma-1)}{2}\right] M_2{}^2\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]}$$

Substituting equation B3 for $M_2{}^2$:

$$\left(\frac{P_{T_2}}{P_1}\right) \quad = \quad \left[\frac{2\gamma M_1{}^2 - (\gamma-1)}{(\gamma+1)}\right]\left(1 + \left[\frac{(\gamma-1)}{2}\right]\left\{\frac{\left[(\gamma-1)M_1{}^2 + 2\right]}{\left[2\gamma M_1{}^2 - (\gamma-1)\right]}\right\}\right)^{\left[\frac{\gamma}{(\gamma-1)}\right]}$$

Defining a supersonic differential pressure, q_c:

$$q_c \quad = \quad \left(P_{T_2} - P_1\right)$$

$$P_{T_2} \quad = \quad q_c + P_1$$

$$\left(\frac{P_{T_2}}{P_1}\right) \quad = \quad \left(\frac{q_c}{P_1}\right) + 1$$

Substituting for $\left(P_{T_2} - P_1\right)$ and rearranging the terms:

$$\left(\frac{q_c}{P_1}\right) + 1 \quad = \quad \left\{\left[\frac{(\gamma-1)^2 M_1{}^2 + 2(\gamma-1)}{4\gamma M_1{}^2 - 2(\gamma-1)}\right] + 1\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]}\left[\frac{1\text{-}\gamma + 2\gamma M_1{}^2}{(\gamma+1)}\right]$$

Replacing 1 on the right side of the equation with $\{[4\gamma M_1{}^2 - 2(\gamma - 1)]/[4\gamma M_1{}^2 - 2(\gamma - 1)]\}$ and moving the 1 on the left side of the equation to the right side produces equation B5.

$$\left(\frac{q_c}{P_1}\right) = \left\{\frac{\left[4\gamma M_1{}^2 - 2(\gamma-1)\right] + \left[(\gamma-1)^2 M_1{}^2 + 2(\gamma-1)\right]}{4\gamma M_1{}^2 - 2(\gamma-1)}\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]} \left[\frac{1\text{-}\gamma + 2\gamma M_1{}^2}{(\gamma+1)}\right] - 1$$

Combining terms on the right side:

$$\left(\frac{q_c}{P_1}\right) = \left\{\frac{\left[(4\gamma + \gamma^2 - 2\gamma+1)M_1{}^2 - \ 2\gamma+2\gamma+ 2 -2\right]}{\left[4\gamma M_1{}^2 - 2(\gamma-1)\right]}\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]} \left[\frac{2\gamma M_1{}^2 - \gamma+1}{(\gamma+1)}\right] - 1$$

$$\left(\frac{q_c}{P_1}\right) = \left\{\frac{(\gamma^2 + 2\gamma+1)M_1{}^2}{\left[4\gamma M_1{}^2 - 2(\gamma-1)\right]}\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]} \left[\frac{2\gamma M_1{}^2 - \gamma+1}{(\gamma+1)}\right] - 1$$

$$\left(\frac{q_c}{P_1}\right) = \left\{\frac{(\gamma+ 1)^2 M_1{}^2}{\left[4\gamma M_1{}^2 - 2(\gamma-1)\right]}\right\}^{\left[\frac{\gamma}{(\gamma-1)}\right]} \left[\frac{2\gamma M_1{}^2 - \gamma+1}{(\gamma+1)}\right] - 1 \qquad \text{(B5)}$$

Substituting 1.4 for γ in equation B5:

$$\left(\frac{q_c}{P_1}\right) = \left[\frac{5.76 M_1{}^2}{5.6 M_1{}^2 - 0.8}\right]^{3.5} \left(\frac{2.8 M_1{}^2 - 0.4}{2.4}\right) - 1$$

Dividing the numerator and the denominator of the first term on the right hand side by 8 and the numerator and the denominator of the second term by 4:

$$\left(\frac{q_c}{P_1}\right) = \left[\frac{0.72 M_1{}^2}{0.7 M_1{}^2 - 0.1}\right]^{3.5} \left(\frac{0.7 M_1{}^2 - 0.1}{0.6}\right) - 1$$

Combining the denominator of the first term with the numerator of the second term:

$$\left(\frac{q_c}{P_1}\right) = \left[\frac{\left(0.72 M_1{}^2\right)^{3.5}}{\left(0.7 M_1{}^2 - 0.1\right)^{2.5}}\right] \left(\frac{1}{0.6}\right) - 1$$

$$\left(\frac{q_c}{P_1}\right) = \frac{\left[(0.72)^{3.5}/0.6\right] M_1{}^7}{\left(0.7 M_1{}^2 - 0.1\right)^{2.5}} - 1$$

Multiplying the first term on the right side of the equation by $\left(\frac{10^{2.5}}{10^{2.5}}\right)$:

$$\left(\frac{q_c}{P_1}\right) = \frac{\left[(0.72)^{3.5}/0.6\right]\left(10^{2.5}\right) M_1{}^7}{\left(0.7 M_1{}^2 - 0.1\right)^{2.5}\left(10^{2.5}\right)} - 1$$

$$\left(\frac{q_c}{P_1}\right) = \left[\frac{(166.921\ 58)\ {M_1}^7}{\left(7{M_1}^2 - 1\right)^{2.5}}\right] - 1$$

Recognizing that P_1 is the freestream ambient air pressure, P_a, and that M_1 is the freestream Mach number produces equation B6.

$$\boxed{\left(\frac{q_c}{P_a}\right) = [(166.921\ 58)M^7/(7M^2 - 1)^{2.5}] - 1} \qquad (B6)$$

This is the supersonic equation relating $\left(\frac{q_c}{P_a}\right)$ and Mach number where:

q_c = (total air pressure sensed behind the shock) - (static air pressure sensed behind the shock)

Substituting M = 1.000 into equation B6:

$$\left(\frac{q_c}{P_a}\right) = 0.892\ 929\ 158$$

Recalling the subsonic equation for (q_c/P_a) as a function of Mach number, equation 59:

$$\left(\frac{q_c}{P_a}\right) = (1 + 0.2M^2)^{3.5} - 1 \qquad (59)$$

Substituting M = 1.000 into equation 59:

$$\left(\frac{q_c}{P_a}\right) = 0.892\ 929\ 159$$

Except for the loss of calculating accuracy in the ninth significant figure, both the subsonic equation (equation 59) and the supersonic equation (equation B6) produce the same value for (q_c/P_a) at M = 1.000.

SUPERSONIC FREESTREAM MACH NUMBER AS A FUNCTION OF (Q_C/P_A)

Starting with equation B6:

$$\boxed{\left(\frac{q_c}{P_a}\right) = [(166.921\ 58)M^7/(7M^2 - 1)^{2.5}] - 1} \qquad (B6)$$

Add 1 to both sides of equation B6 and then multiply both sides by $(7M^2 - 1)^{2.5}$:

$$\left[\left(\frac{q_c}{P_a}\right) + 1\right](7M^2 - 1)^{2.5} = (166.921\ 58)\ M^7$$

Divide both sides by $(7M^2)^{2.5}$:

$$\left[\left(\frac{q_c}{P_a}\right)+\ 1\right]\left[\frac{(7M^2-1)}{7M^2}\right]^{2.5} \qquad = \qquad (1.287\ 559\ 74)\ M^2$$

Divide by the constant on the right side and take the square root produces equation B7.

$$M \qquad = \qquad \left\{(0.776\ 663\ 0)\left[\left(\frac{q_c}{P_a}\right)+\ 1\right]\left[1-\ \left(\frac{1}{7M^2}\right)\right]^{2.5}\right\}^{0.5} \qquad \text{(B7)}$$

Or pulling the constant out of the square root produces equation B8.

$$\boxed{M \qquad = \qquad (0.881\ 284\ 85)\left\{\left[\left(\frac{q_c}{P_a}\right)+\ 1\right]\left[1-\ \left(\frac{1}{7M^2}\right)\right]^{2.5}\right\}^{0.5}} \qquad \text{(B8)}$$

Equations B7, B8, and B9 must be solved iteratively.

SUPERSONIC CALIBRATED AIRSPEED AS A FUNCTION OF Q_C

Starting with equation B8:

$$\boxed{M \qquad = \qquad (0.881\ 284\ 85)\left\{\left[\left(\frac{q_c}{P_a}\right)+\ 1\right]\left[1-\ \left(\frac{1}{7M^2}\right)\right]^{2.5}\right\}^{0.5}} \qquad \text{(B8)}$$

Replace Mach number, M, with (V_c/a_{SL}) and P_a with P_{SL} produces equation B9.

$$\frac{V_c}{a_{SL}} \qquad = \qquad (0.881\ 284\ 85)\left(\left[\left(\frac{q_c}{P_{SL}}\right)+\ 1\right]\left\{1-\left[\frac{1}{7\left(\frac{V_c}{a_{SL}}\right)^2}\right]\right\}^{2.5}\right)^{0.5}$$

$$\boxed{V_c \qquad = \qquad (0.881\ 284\ 85)a_{SL}\left(\left[\left(\frac{q_c}{P_{SL}}\right)+1\right]\left\{1-\left[\frac{1}{7\left(\frac{V_c}{a_{SL}}\right)^2}\right]\right\}^{2.5}\right)^{0.5}} \qquad \text{(B9)}$$

Note: In this supersonic case, q_c is not equal to $(P_T - P_a)$; it is equal to the differential pressure measured behind the normal shock.

SUPERSONIC Q_C AS A FUNCTION OF CALIBRATED AIRSPEED

Starting with equation B6:

$$\boxed{\left(\frac{q_c}{P_a}\right) \quad = \quad [(166.921\,58)M^7/(7M^2 - 1)^{2.5}] - 1} \tag{B6}$$

Replace Mach number, M, with (V_c/a_{SL}) and P_a with P_{SL} produces equation B10.

$$\left(\frac{q_c}{P_{SL}}\right) = \left\{(166.921\,58)\left(\frac{V_c}{a_{SL}}\right)^7 / \left[7\left(\frac{V_c}{a_{SL}}\right)^2 - 1\right]^{2.5}\right\} - 1$$

$$\boxed{q_c = P_{SL}\left(\left\{(166.921\,58)\left(\frac{V_c}{a_{SL}}\right)^7 / \left[7\left(\frac{V_c}{a_{SL}}\right)^2 - 1\right]^{2.5}\right\} - 1\right)} \tag{B10}$$

APPENDIX C - SPECIFIC GAS CONSTANT FOR DRY AIR

SPECIFIC GAS CONSTANT FOR DRY AIR

The specific gas constant, R, for dry air is used throughout this handbook. It is the ratio of the universal gas constant, R*, divided by the molecular weight for dry air, M.

1976 U.S. STANDARD ATMOSPHERE

In table 2 on page 2 and again on page 3 of reference 1, a value for R* of 8,314.32 $(kg \cdot m^2)/(sec^2 \cdot K \cdot kmol)$ was identified. Reference 1 did not present a value for the specific gas constant. The molecular weight for dry air on page 9 was 28.964 4 (kg/kmol) to 6 significant figures. It did present, in table 3 on page 3, information that could be used to calculate the molecular weight using equation 21 on page 9 of reference 1 and therefore the specific gas constant. That information was extracted and is included in this handbook as table C1. The molecular weight determined using table C1 was 28.964 505 (kg/kmol), similar to the value presented above to four significant figures. Those values for R* and for M result in a value for R of:

Assuming R* = 8,314.32 $(kg \cdot m^2)/(sec^2 \cdot K \cdot kmol)$ and M = 28.964 51 (kg/kmol):

$$R = 287.051\,98\ (m/sec)^2/K$$

$$= 3{,}089.801\,8\ (ft/sec)^2/K$$

$$= 1{,}716.556\,6\ (ft/sec)^2/(deg\ R)$$

$$= 53.352\,206\ ft/(deg/R)$$

Table C1 Estimating the Molecular Weight of Dry Air for the 1976 U.S. Standard Atmosphere Model

Gas Species	Molecular Weight (kg/kmol)	Fractional volume (dimensionless)	Molecular Weight (kg/kmol)
N_2	28.0134	0.78084	21.87398
O_2	31.9988	0.209476	6.70298
Ar	39.948	0.00934	0.37311
CO_2	44.00995	0.000314	0.01382
Ne	20.183	0.00001818	0.00037
He	4.0026	0.00000524	0.00002
Kr	83.80	0.00000114	0.00010
Xe	131.30	0.000000087	0.00001
CH_4	16.04303	0.000002	0.00003
H_2	2.01594	0.0000005	0.00000
	Total	0.999 997 06	28.96442

Notes: 1. Data from table 3 on page 3 of 1976 U.S. Atmosphere book, reference 1.
2. (28.964 42)/(0.999 997 06) = 28.964 505
3. Abbreviations, acronyms, and symbols are defined in appendix H.

CONSISTENCY CHECKS

1976 U.S. Standard Atmosphere:

Reference 1 provides the following information in table 10 on page 20 that can be used to calculate the value for the specific gas constant for dry air used by the 1976 U.S. standard atmosphere. These are values for pressure, temperature, density, and the speed of sound at sea level.

$$P = 101{,}325\ (\mathrm{N/m^2})$$

$$T = 288.15\ \mathrm{K}$$

$$\rho = 1.2250\ (\mathrm{kg/m^3})$$

$$a = 340.294\ (\mathrm{m/sec})$$

Assuming a perfect gas and using the speed of sound equation:

$$a = (\gamma RT)^{0.5}$$

where γ is the dimensionless ratio of specific heats.

$$a^2 = \gamma RT$$

$$R = \frac{a^2}{\gamma T}$$

For $\gamma = 1.40$ (exact), R must be:

$$R = \frac{(340.294)^2 (\mathrm{m/sec})^2}{1.40(288.15)\mathrm{K}}$$

$$R = 287.052\ 890 \left(\frac{\mathrm{m}^2}{\mathrm{sec}^2 \cdot \mathrm{K}}\right)$$

Alternatively, using the perfect gas equation:

$$P = \rho RT$$

$$R = \frac{P}{\rho T}$$

$$R = \frac{101{,}325(\ \mathrm{N/m^2})}{1.2250\ (\mathrm{kg/m^3})\ 288.15\ \mathrm{K}}$$

Note: 1 (N) = 1 (kg $\cdot$ m/sec^2)

$$R \quad = \quad 287.052\ 874 \left(\frac{m^2}{sec^2 \cdot K}\right)$$

The 1976 U.S. standard atmosphere value for the specific gas constant for dry air (to seven significant figures) is 287.052 9 $(m/sec)^2/K$.

1993 ICAO International Standard Atmosphere:

Table A on page E-viii and in table C on page E-xi of reference 3 documents the constants in table C2 for the 1993 ICAO international standard atmosphere:

Table C2 Sea Level Constants for the 1993 ICAO International Standard Atmosphere

Parameter	Units	Value
Ambient Air Pressure, P	$kg/(m \cdot sec^2)$	101,325
Ambient Air Temperature, T	K	288.15
Ambient Air Density, ρ	kg/m^3	1.225
Universal Gas Constant, R*	$kg \cdot (m/sec)^2 \cdot K \cdot kmol$	8,314.32
Molecular Weight, M	kg/kmol	28.964 420
Specific Gas Constant, R	$(m/sec)^2/K$	287.052 87
Speed of Sound, a	m/sec	340.294

Note: Abbreviations, acronyms, and symbols are defined appendix H.

Note that the sea level constants for pressure, temperature, density, speed of sound, and the universal gas constant are identical for the two atmospheres. The molecular weight for the 1993 ICAO international standard atmosphere is similar to that calculated using the information in reference 1. The specific gas constant calculated using the information in table 3 of reference 1 resulted in a similar specific gas constant for both atmospheres. The gas constant calculated using P = 1013.25 millibars, T= 288.15 K, and an ambient air density of 1.2250 (kg/m^3) matched the 1993 ICAO value within 0.000 004 $(m/sec)^2/K$, an insignificant difference. The ICAO value for the gas constant would have required an ambient air density of 1.225 000 018 (kg/m^3) vice 1.225 000 000, again an insignificant difference.

The gas constant calculated using 340.294 (m/sec) for the speed of sound, 1.40 for the dimensionless ratio of specific heats, and 288.15 K for the ambient air temperature was 0.000 02 $(m/sec)^2/K$ larger than the ICAO value. A value for R of 287.052 87 $(m/sec)^2/K$ would have resulted in a calculated speed of sound of 340.293 988 (m/sec) vice the ICAO value of 340.294 000, an insignificant difference of 0.000 012 (m/sec).

SUMMARY

It was assumed for the remainder of this handbook that the ICAO value for the specific gas constant for dry air, 287.052 87 $(m/sec)^2/K$, was correct.

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APPENDIX D – SENSITIVITY STUDIES OF THE RESOLUTIONS OF THE CONSTANTS

TROPOSPHERE

The number of significant figures used in most college textbooks is less than those shown in equations 30 through 34. The sensitivity studies presented in tables D1 and D2 show that at least five significant figures should be used with these equations.

Table D1 The Effect of the Resolution of (6.875 585 7 x 10^{-6})
in Equation 33 for 36,089. 239 Geopotential Feet

Resolution (10^{-6}/ft)	Calculated Ambient Air Pressure Ratio, δ (n/d)
6.875 585 7	0.223 360 9
6.875 585	0.223 360 9
6.875 59	0.223 360 6
6.875 58	0.223 361 2
6.875 6	0.223 360 0
6.876	0.223 337 5
6.88	0.223 112 2
6.9	0.221 988 5
7	0.216 438 7

Notes: 1. The calculated ambient air pressure ratios are the same to five significant figures, 0.223 36, when using at least five significant figures for the value of the temperature lapse rate divided by the ambient temperature at sea level.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

Table D2 The Effect of the Resolution of the Exponent,
0.190 263 1, in Equation 34 on the Calculated
Pressure Altitude for δ = 0.223 361

Resolution (n/d)	Calculated Pressure Altitude (ft)
0.190 263 103	36,089. 23
0.190 263 10	36,089. 23
0.190 263 1	36,089. 23
0.190 263	36,089. 21
0.190 26	36,088. 72
0.190 3	36,095. 28
0.190	36,046. 09
0.19	36,046. 09
0.2	37,673. 67

Notes: 1. Using 0.190 263 103 as the exponent and 0.223 360 9 for δ results in a pressure altitude of 36,089.237 vice 36,089.239 feet.
2. Abbreviations, acronyms, and symbols are defined in appendix H.

Equation 30 with SI units was used to compare against the tabular data in references 1 and 3 for the 1976 U.S. standard atmosphere and the 1993 ICAO international standard atmosphere, table D3. The calculated results from equation 30 with seven significant figures, when rounded off to six significant figures, were identical to the six significant figures in reference 3 for the 1993 ICAO international standard atmosphere.

Table D3 Ambient Air Pressure Ratios, δ, for the Troposphere

Geopotential Height (1,000 m)	Ambient Air Pressure Ratio, δ - (n/d)		
	1976 U.S. Standard Atmosphere	1993 ICAO Standard Atmosphere	Equation 30
0	1.000 00	1.000 000	1.000 000 0
1	0.886 99	0.886 993	0.886 993 0
2	0.784 55	0.784 557	0.784 556 6
3	0.691 91	0.691 917	0.691 917 3
4	0.608 34	0.608 342	0.608 341 6
5	0.533 13	0.533 135	0.533 134 8
6	0.465 64	0.465 640	0.465 640 3
7	0.405 23	0.405 238	0.405 237 8
8	0.351 34	0.351 343	0.351 342 5
9	0.303 40	0.303 404	0.303 404 2
10	0.260 90	0.260 905	0.260 905 4
11	0.223 36	0.223 361	0.223 360 9

Notes:
1. The 1976 U.S. standard atmosphere values with five significant figures appear to be the equivalent of having been truncated from the 1993 ICAO values with six significant figures.
2. The values calculated using equation 30 are identical to those of the 1993 ICAO international standard atmosphere to at least the first six significant figures.
3. Abbreviations, acronyms, and symbols are defined in appendix H.

The values in reference 1, with five significant figures, appear to be the equivalent of truncated values relative to either the 1993 ICAO values or the values calculated with equation 30.

<u>Stratosphere:</u>

The stratosphere ranges from 11,000 to 20,000 meters, 36,089.239 to 65,616.798 feet. If we use H = 36,089.239 feet in equation 45, then $e^0 = 1$ and δ is the correct value for 11,000 meters. If we use H = 65,616.798 feet, the calculated δ is 0.054 032 84. The 1993 ICAO value for 20,000 meters from reference 3 is 0.054 032 8, an agreement with the calculated value through the first six significant figures.

If we use δ = 0.223 360 9, the value for 36,089. 239 feet, in equation 46, then the natural log term is ln (1.000 004 037). The natural log is 0.000 004 037 (it should be exactly zero) and equation 46 produces a value for geopotential height of 36, 089.153 feet, an answer in error by only 0.084 foot or only 1.01 inch. If we use δ = 0.054 032 8, the ICAO value for 20,000 meters, then equation 46 produces an altitude of 65, 616.731 feet with an error of 0.067 foot or 0.80 inch.

APPENDIX E – QUICK REFERENCE FOR SUBSONIC RELATIONSHIP EQUATIONS

SUBSONIC RELATIONSHIP EQUATIONS

Sea Level Standard Day Reference Conditions

Parameter	U.S. Customary Units
P_{SL}	2116.2167 (lb/ft^2)
a_{SL}	661.4786177 (knots)
T_{SL}	288.15 (k)
ρ_{SL}	

Ambient Pressure Ratio	Ambient Temperature Ratio	Ambient Density Ratio	Total Pressure	Ambient Air Temperature	Total Temperature
$\delta = \frac{P_a}{P_{SL}}$	$\theta = \frac{T}{T_{SL}}$ (eq. 77)	$\sigma = \frac{\rho}{\rho_{SL}}$	$P_T = P_a + q_c$	$T_a = f(T_{Tic}, M, K_r)$ (eq. 85)	$T_T = f(T_a, M)$ (eq. 86)
$\delta = f(V_C, M)$ (eq. 159)				$T_a = f(T_T, M)$ (eq. 87)	$T_T = f(T_{Tic}, M, K_r)$ (eq. 89)

Parameter	For: Pressure Altitude < 36,089 Feet	For : 36,089 Feet <= Pressure Altitude < 65,617 Feet
Ambient Pressure Ratio	$\delta = f(h_p)$ (eq. 33)	$\delta = f(h_p)$ (eq. 45)
Pressure Altitude	$h_p = f(\delta)$ (eq. 34)	$h_p = f(\delta)$ (eq. 46)

Pressures as a Function of Mach Number

$\frac{P_T}{P_A} = F(M)$	(eq. 56)
$\frac{q_C}{P_a} = f(M)$	(eq. 67)

Incompressible Dynamic Pressure	
$q = f(M, \delta)$	(eq. 123)
Compressible Dynamic Pressure	
$q_C = f(M, \delta)$	(eq. 72)
$q_C = f(v_c)$	(eq. 143)

Mach Number	**Calibrated Airspeed**	**Equivalent Airspeed**	**True Airspeed**
$M = \frac{V_T}{a}$	$V_C = f(q_C) \int (q_C)$ (eq. 131)	$V_e = V_T \sqrt{\sigma}$ (eq. 108)	$V_T = \frac{M}{a}$ (eq. 73)
$M = f\left(\frac{P_T}{P_a}\right)$ (eq. 60)	$V_C = f(q_C)$ (eq.136)	$V_e = f(q_c, P_a)$ (eq. 107)	$V_T = f(\rho, P_a, P_T)$ (eq.95)
$M = f\left(\frac{q_{cT}}{P_a}\right)$ (eq. 65)	$V_C = f(M, \delta)$ (eq. 154)	$V_e = f(M, \delta)$ (eq. 129)	$V_T = f(\rho, P_a, q_C)$ (eq.97)
$M = f(V_e, \delta)$ (eq. 130)			$V_T = f(\theta, P_a, q_C)$ (eq.100)
$M = f(V_C, \delta)$ (eq. 158)			$V_T = f(\theta, q_C, P_a)$ (eq. 102)
			$V_T = f(\theta, M)$ (eq. 106)

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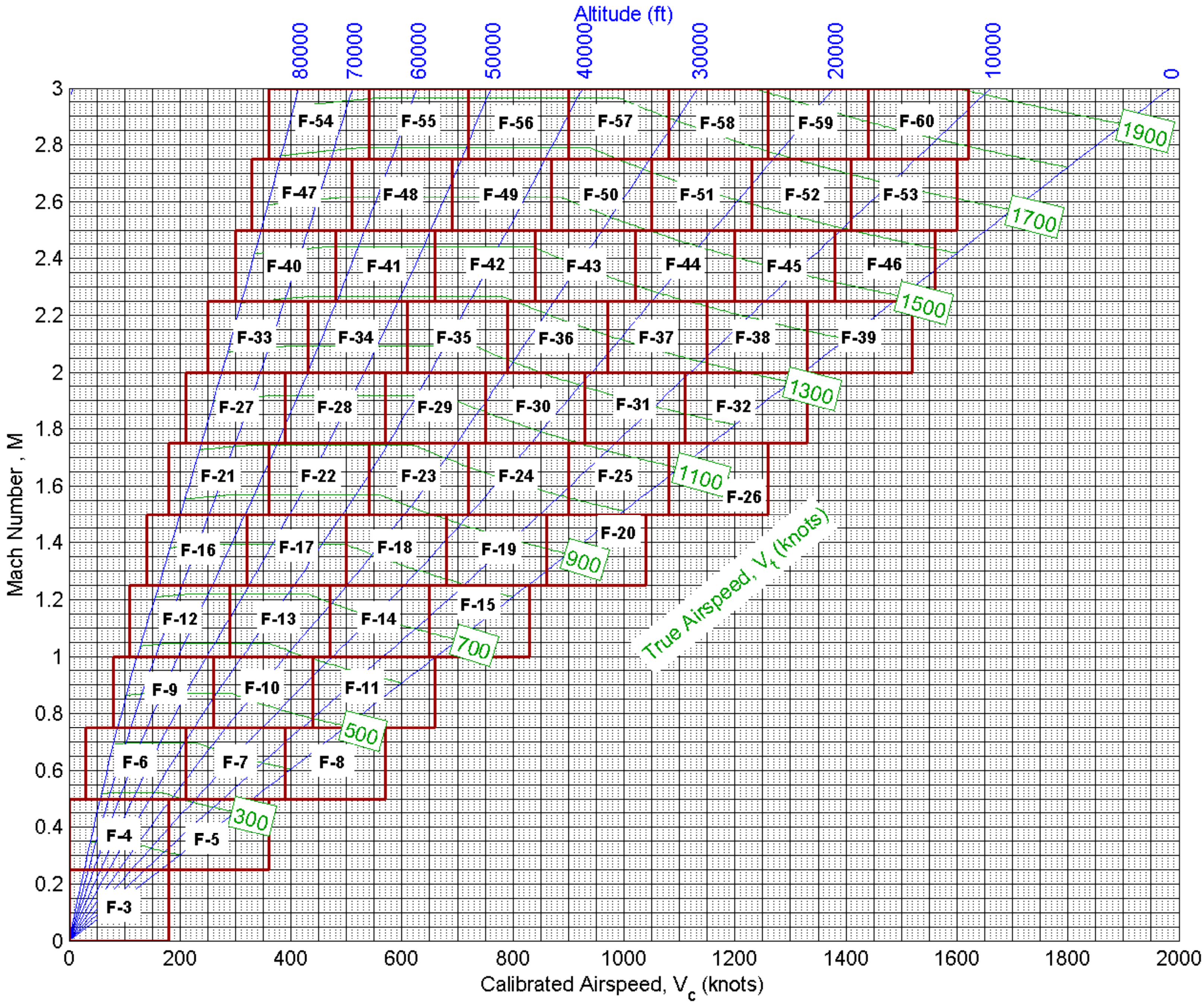
APPENDIX F – GRAPHS OF PRESSURE ALTITUDE, CALIBRATED AIRSPEED, AND MACH NUMBER FOR BOTH SUBSONIC AND SUPERSONIC FLIGHT CONDITIONS



Altitude (ft)
80000
70000
60000
50000
40000
30000
20000
10000
0
Mach Number , M
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
300
500
700
900
1100
1300
1500
1700
1900
F-3
F-4
F-5
F-6
F-7
F-8
F-9
F-10
F-11
F-12
F-13
F-14
F-15
F-16
F-17
F-18
F-19
F-20
F-21
F-22
F-23
F-24
F-25
F-26
F-27
F-28
F-29
F-30
F-31
F-32
F-33
F-34
F-35
F-36
F-37
F-38
F-39
F-40
F-41
F-42
F-43
F-44
F-45
F-46
F-47
F-48
F-49
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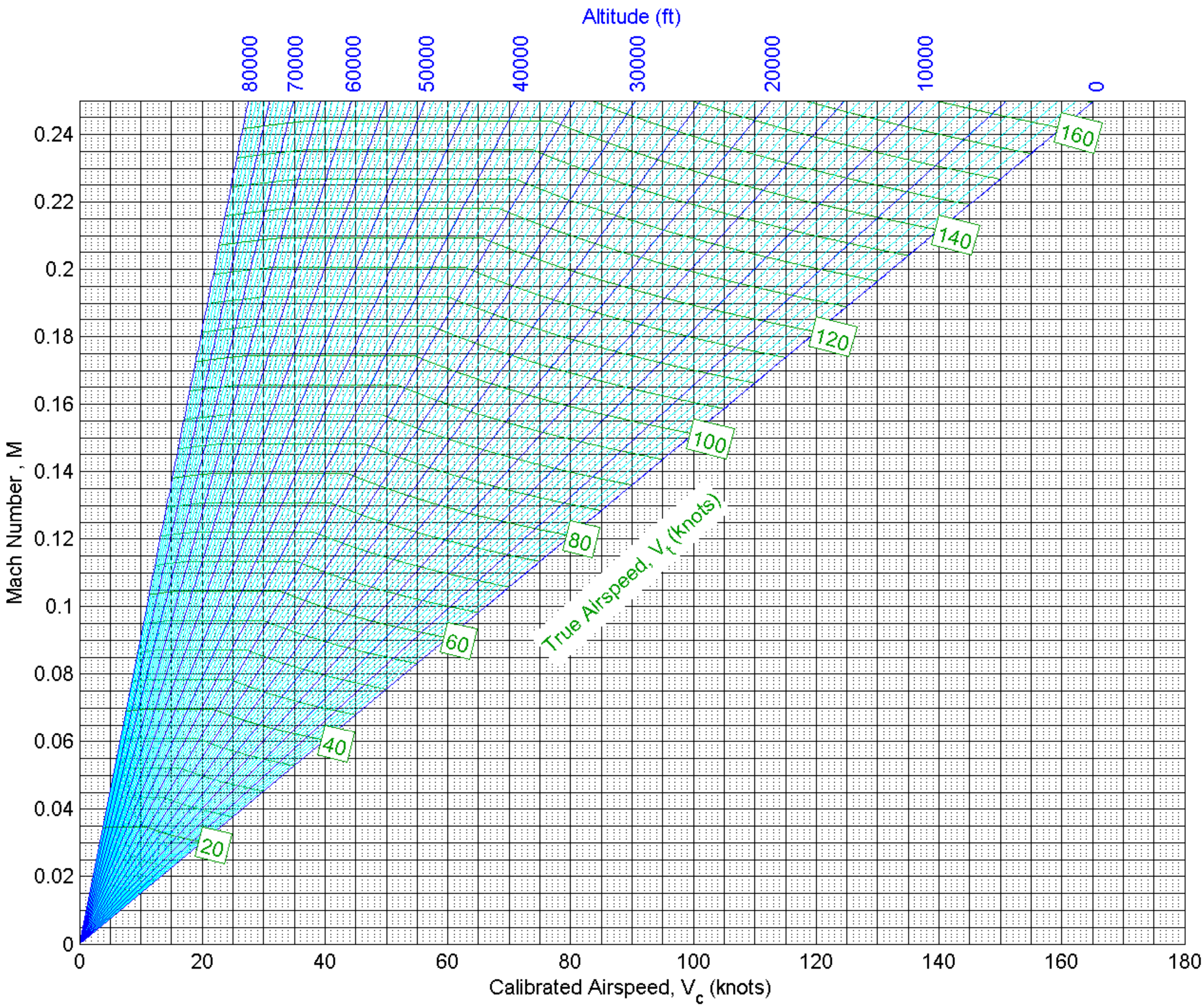
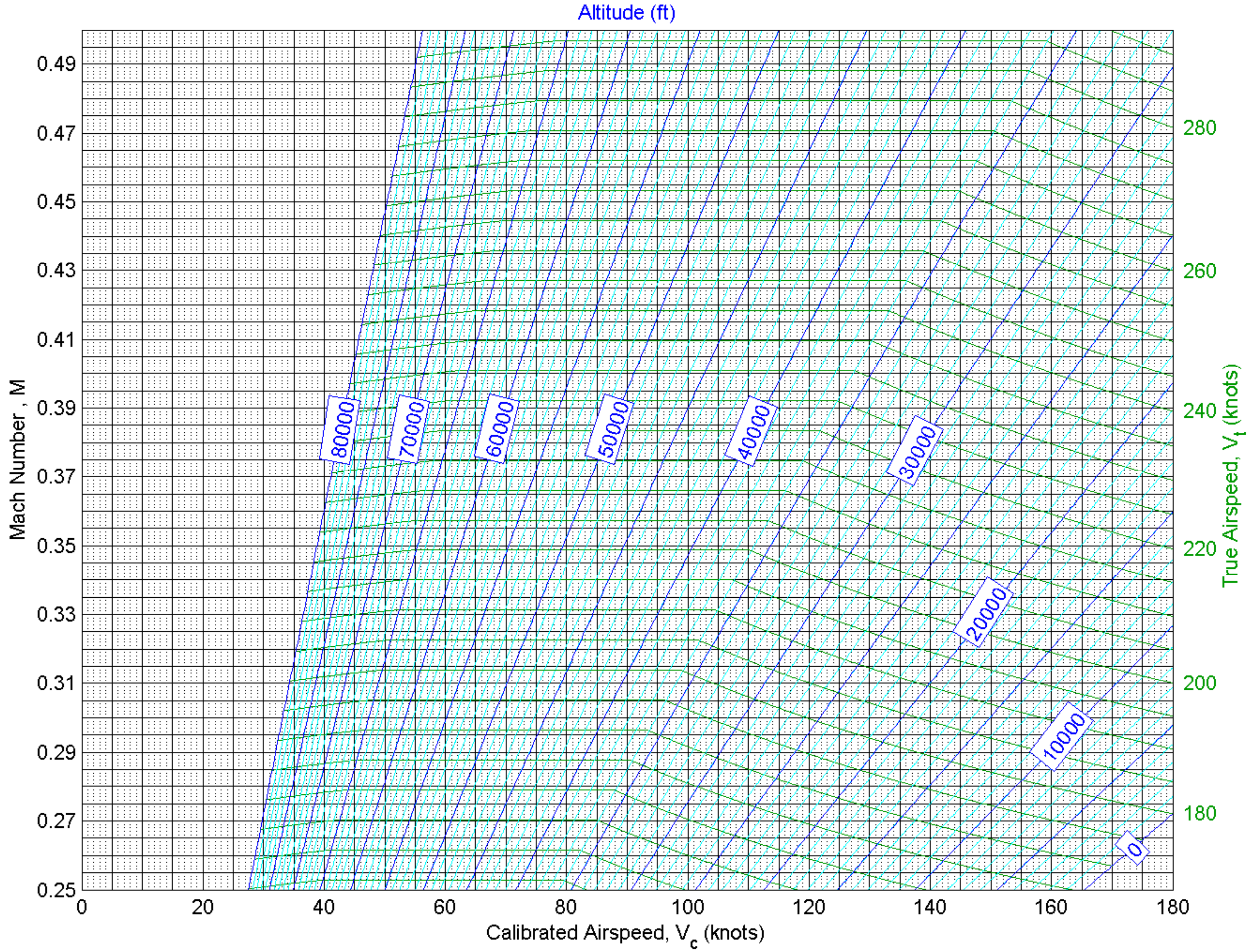
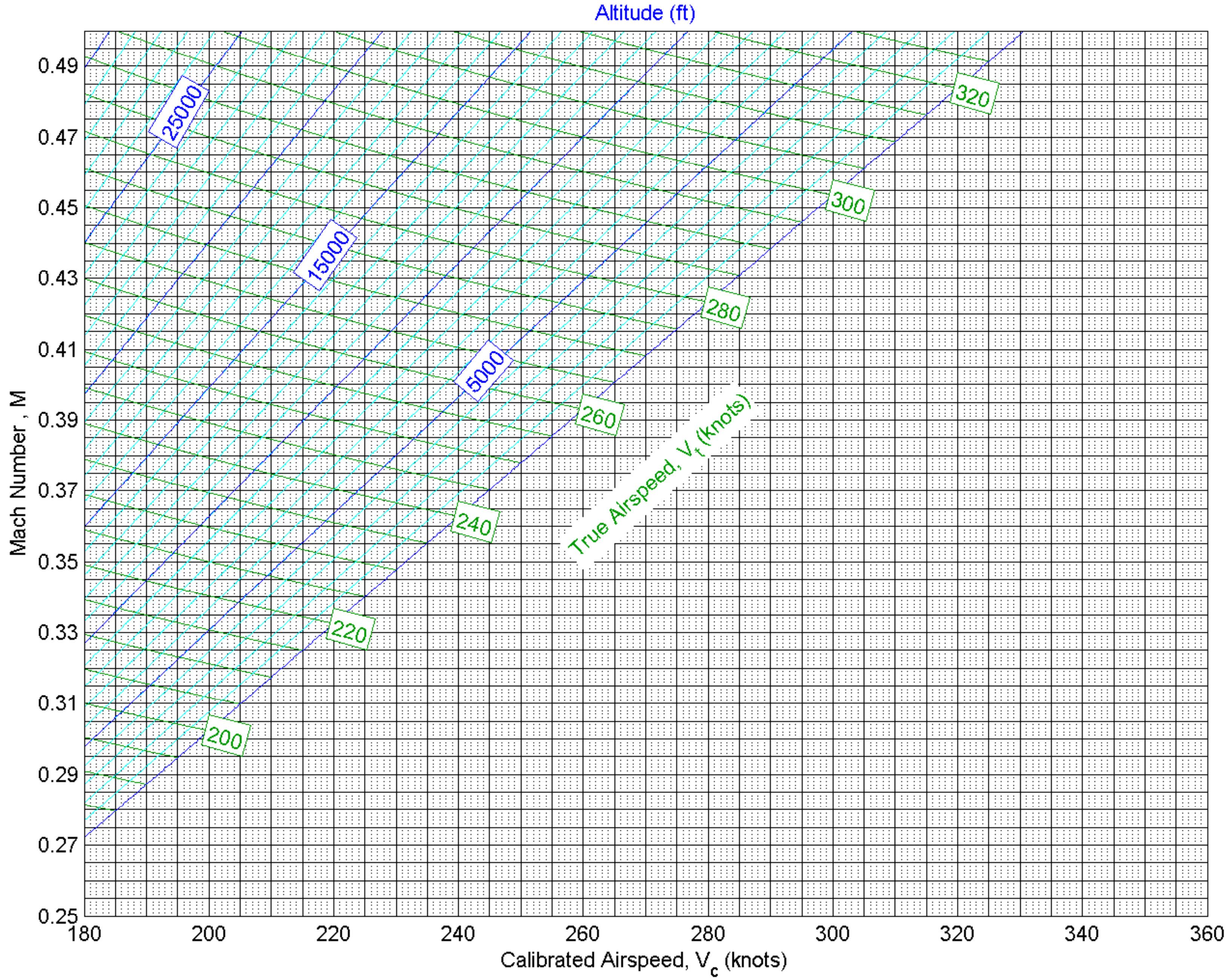
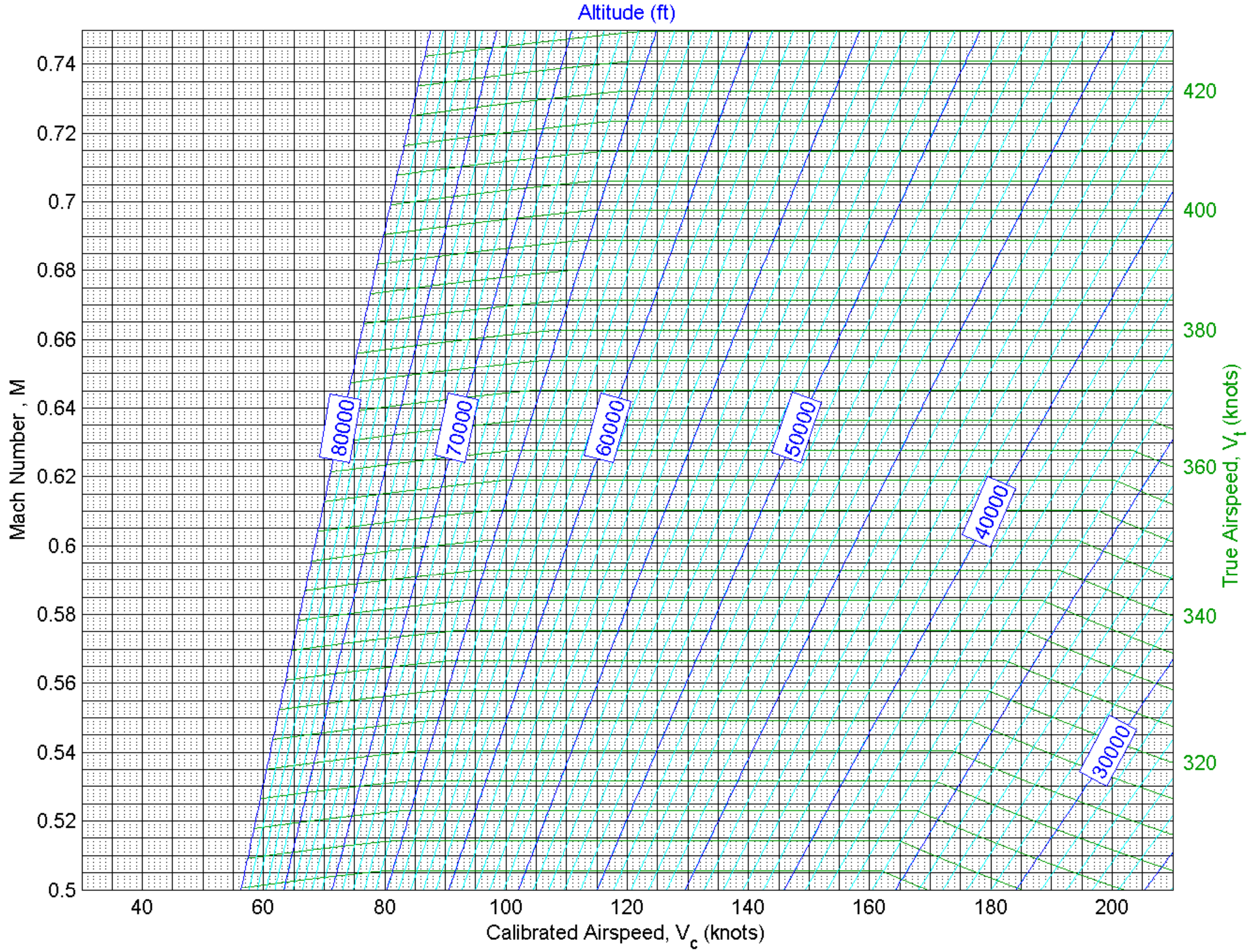
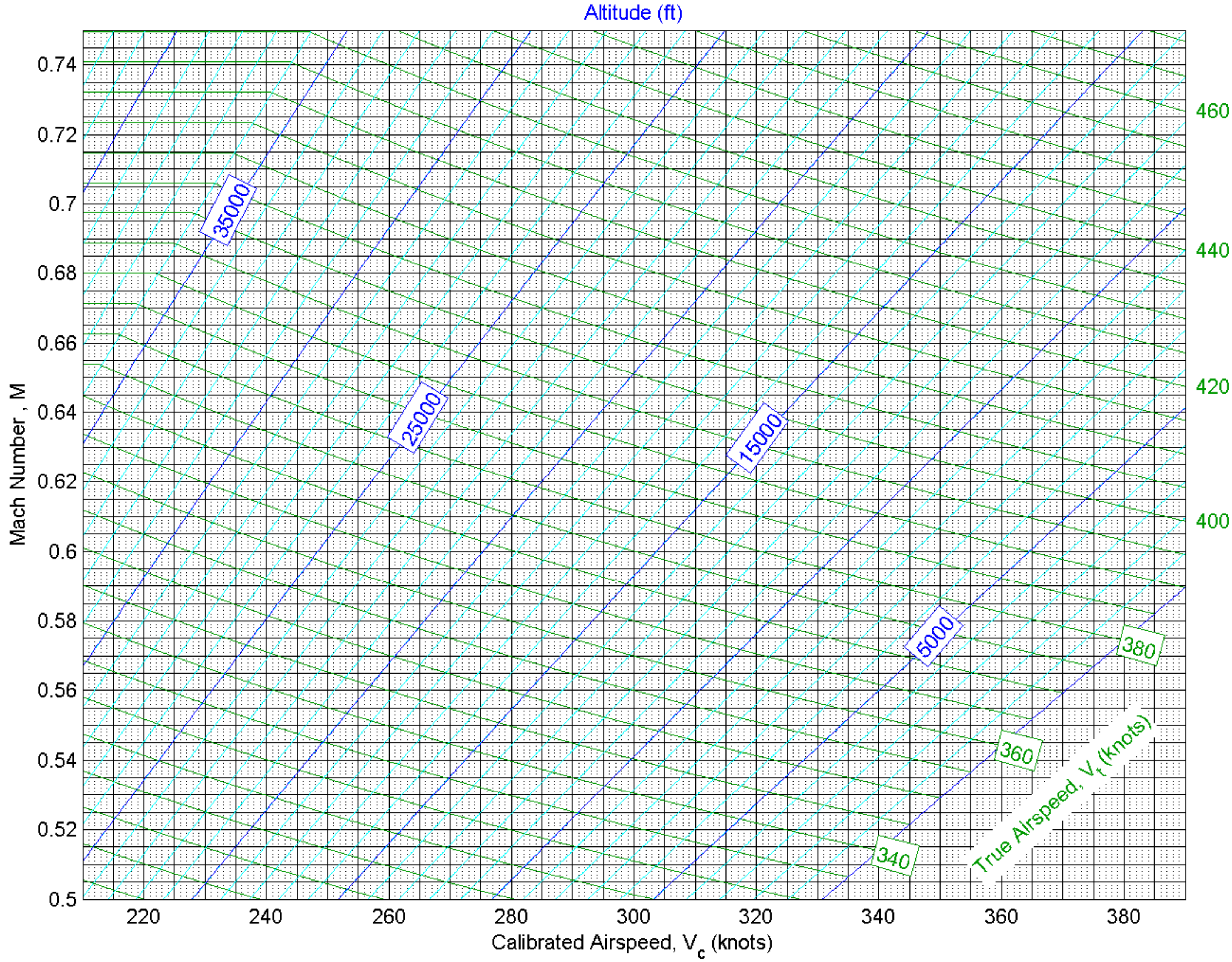
F-57
F-58
F-59
F-60

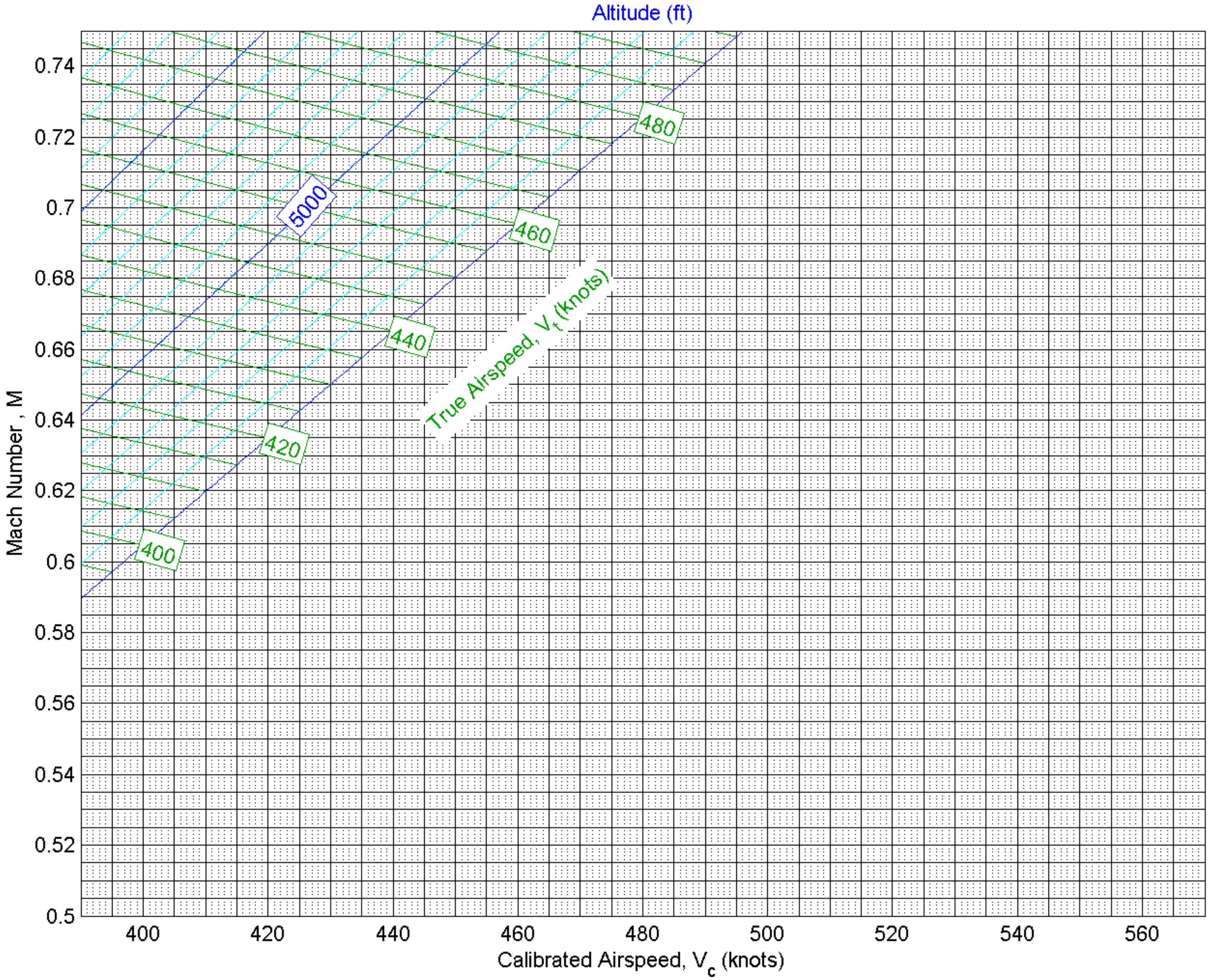

Altitude (ft)
80000
70000
60000
50000
40000
30000
20000
10000
0
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Mach Number , M
160
140
120
100
80
60
40
20
True Airspeed, V_t (knots)
0
20
40
60
80
100
120
140
160
180
Calibrated Airspeed, V_c (knots)

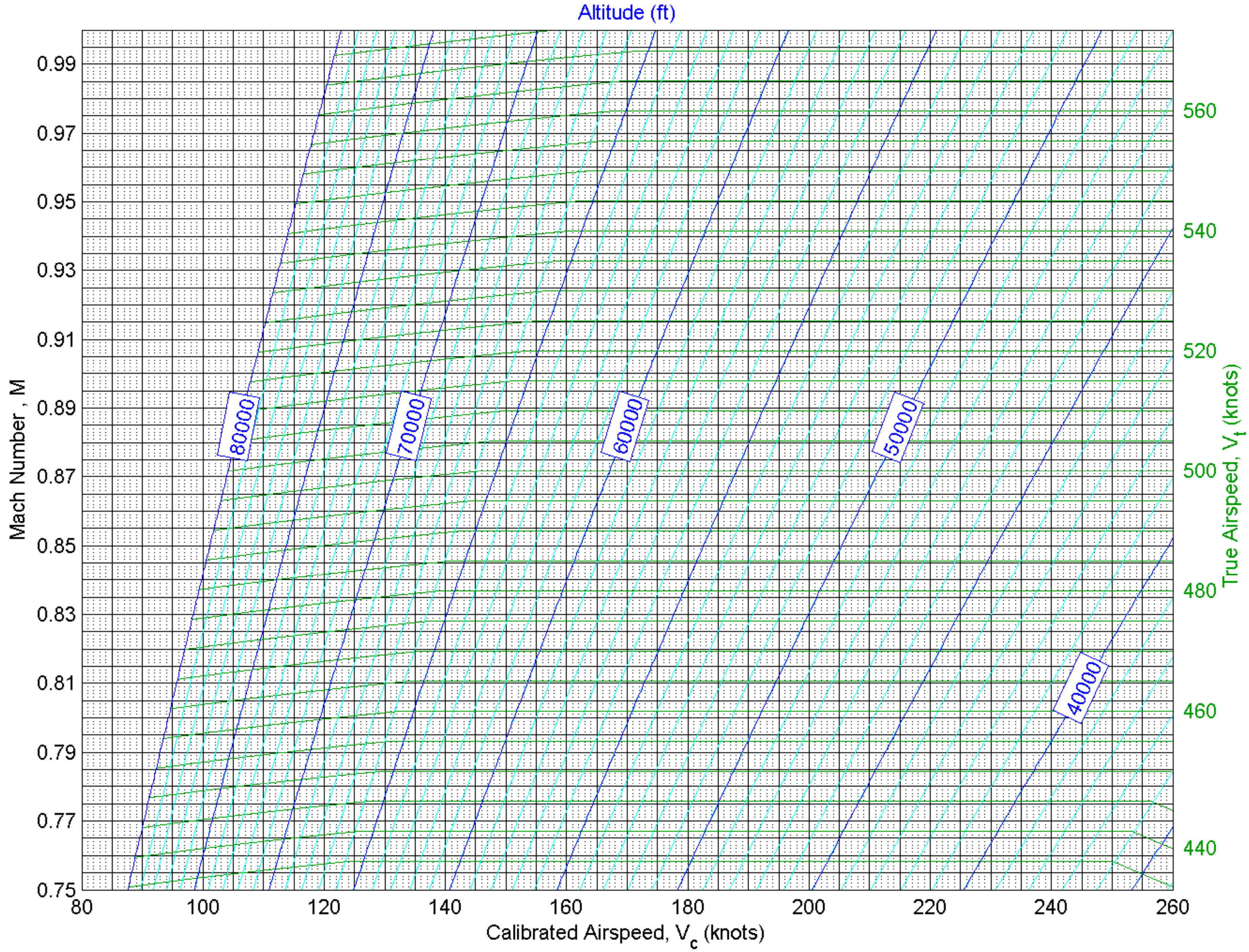

Altitude (ft)
Mach Number, M
0.25
0.27
0.29
0.31
0.33
0.35
0.37
0.39
0.41
0.43
0.45
0.47
0.49
0
20
40
60
80
100
120
140
160
180
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
180
200
220
240
260
280
80000
70000
60000
50000
40000
30000
20000
10000
0

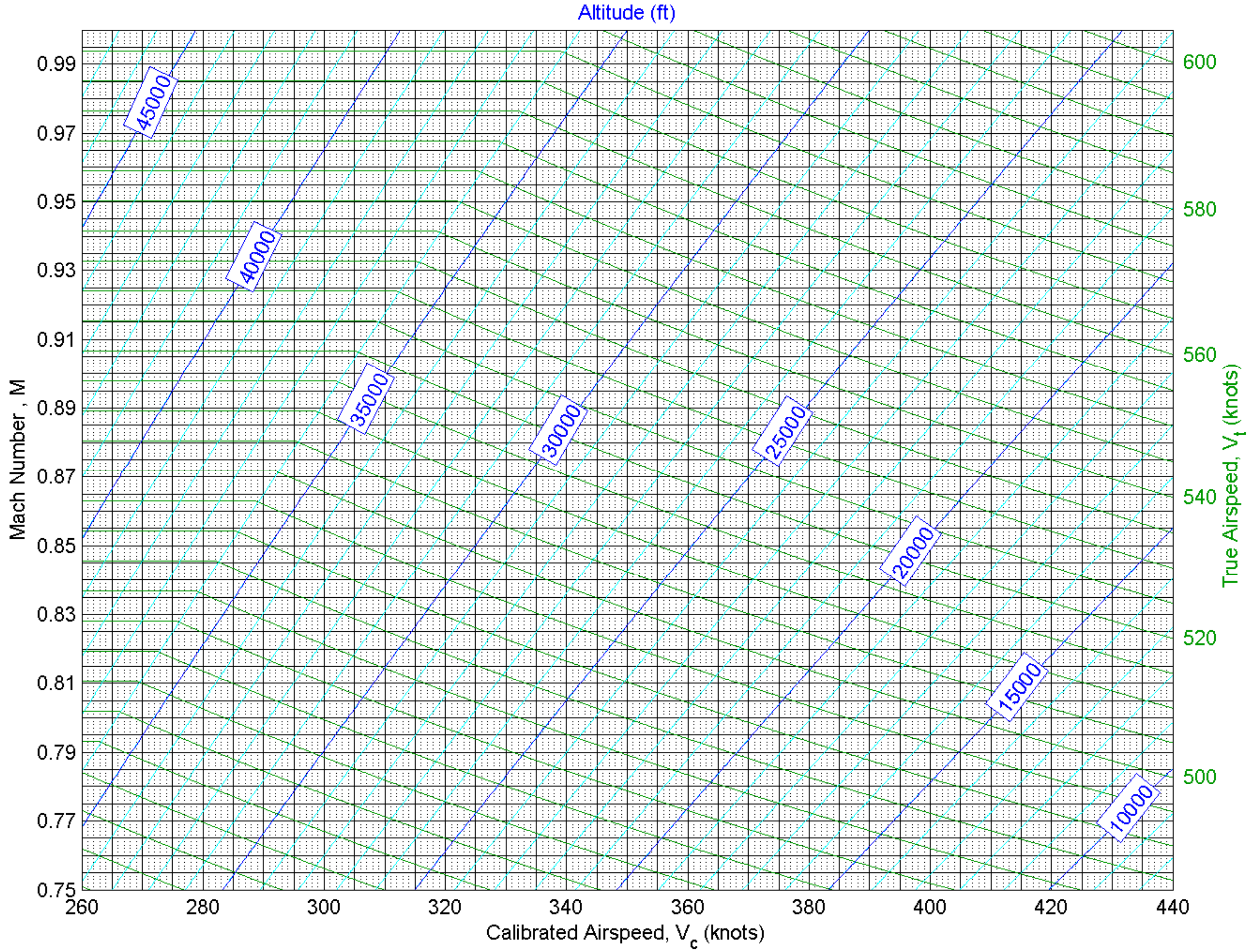

Altitude (ft)
25000
15000
5000
True Airspeed, V_t (knots)
200
220
240
260
280
300
320
Mach Number , M
0.25
0.27
0.29
0.31
0.33
0.35
0.37
0.39
0.41
0.43
0.45
0.47
0.49
Calibrated Airspeed, V_c (knots)
180
200
220
240
260
280
300
320
340
360

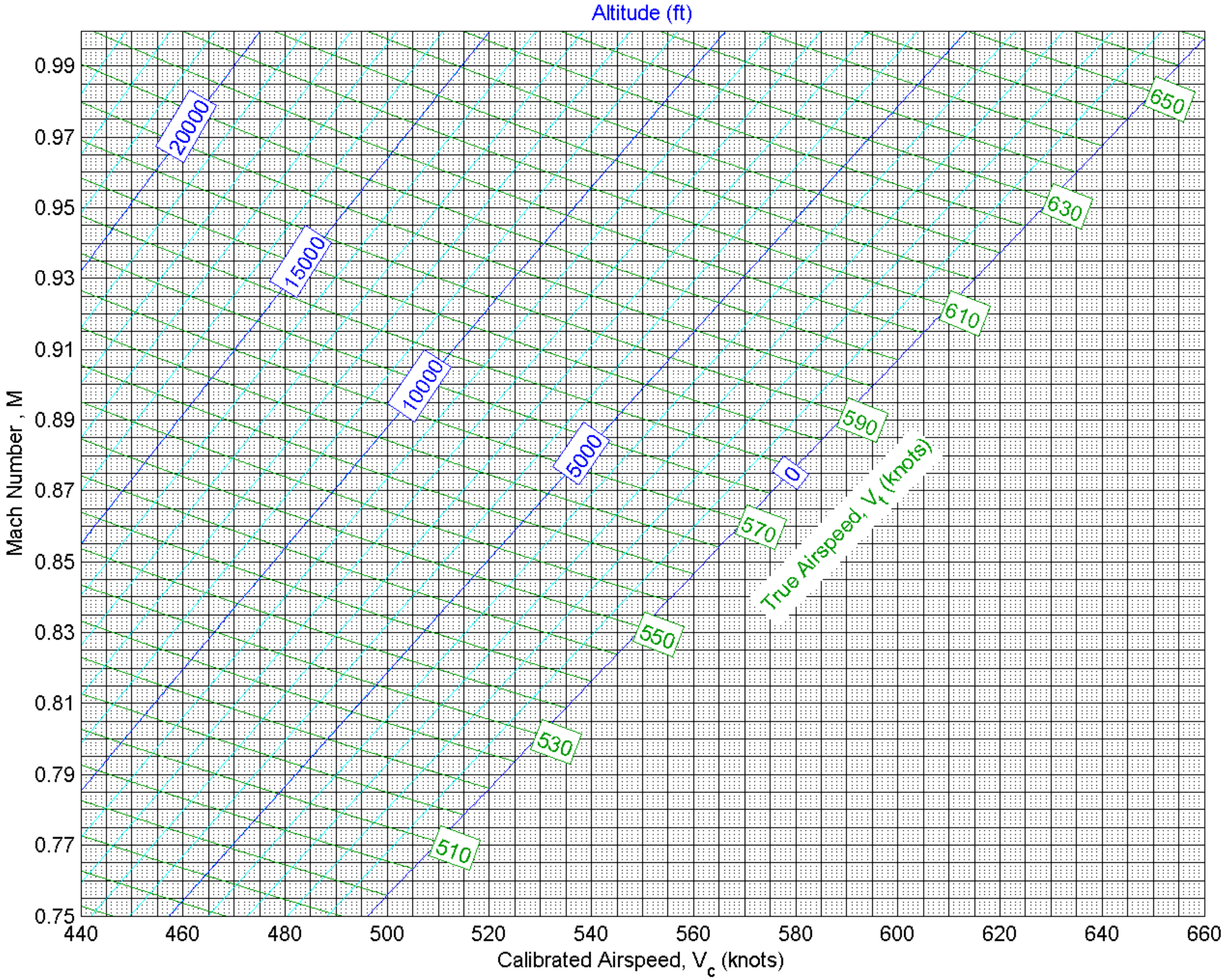

Altitude (ft)
80000
70000
60000
50000
40000
30000
Mach Number, M
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0.52
0.5
40
60
80
100
120
140
160
180
200
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
420
400
380
360
340
320

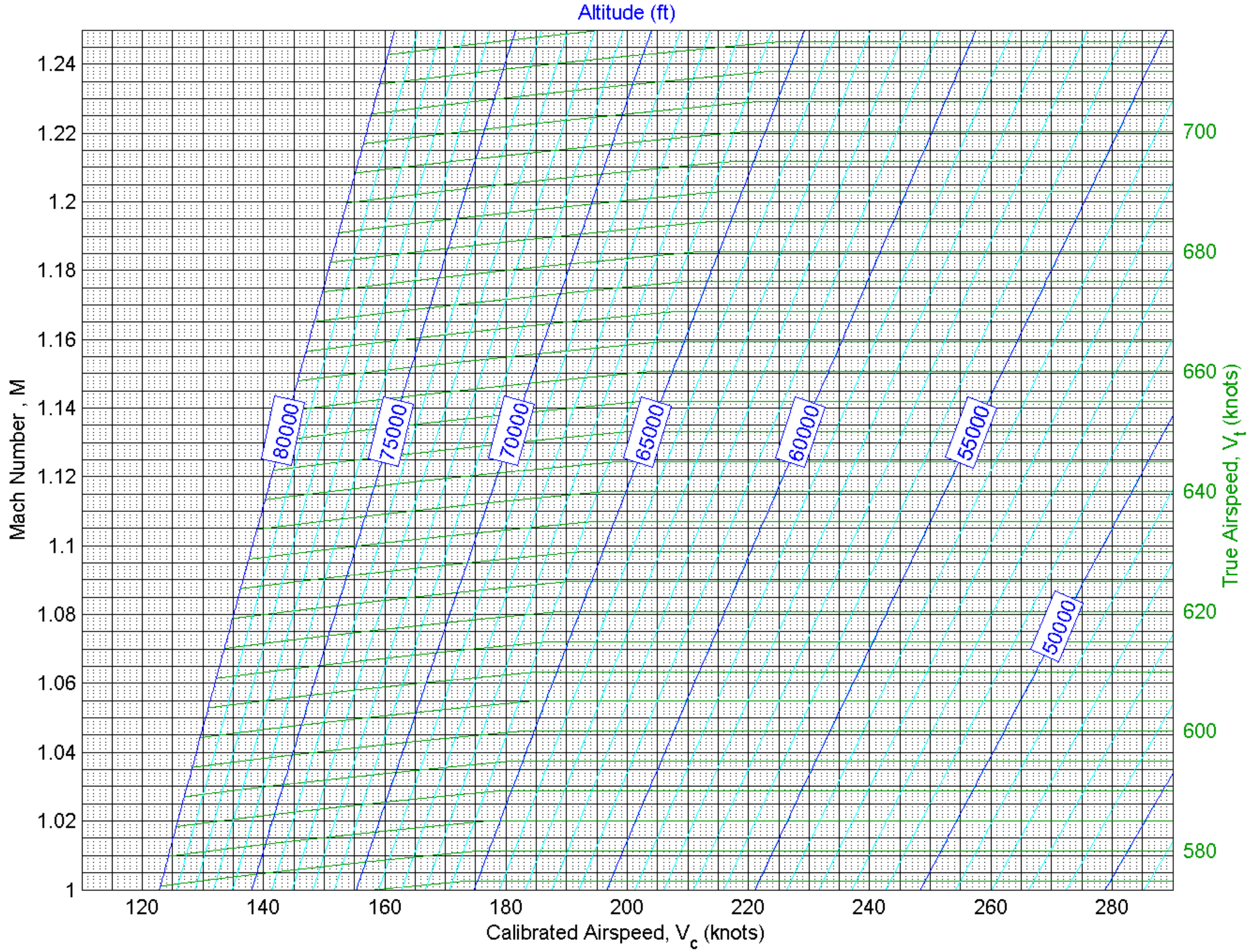

Altitude (ft)
Mach Number, M
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
35000
25000
15000
5000
340
360
380
400
420
440
460
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
220
240
260
280
300
320
340
360
380

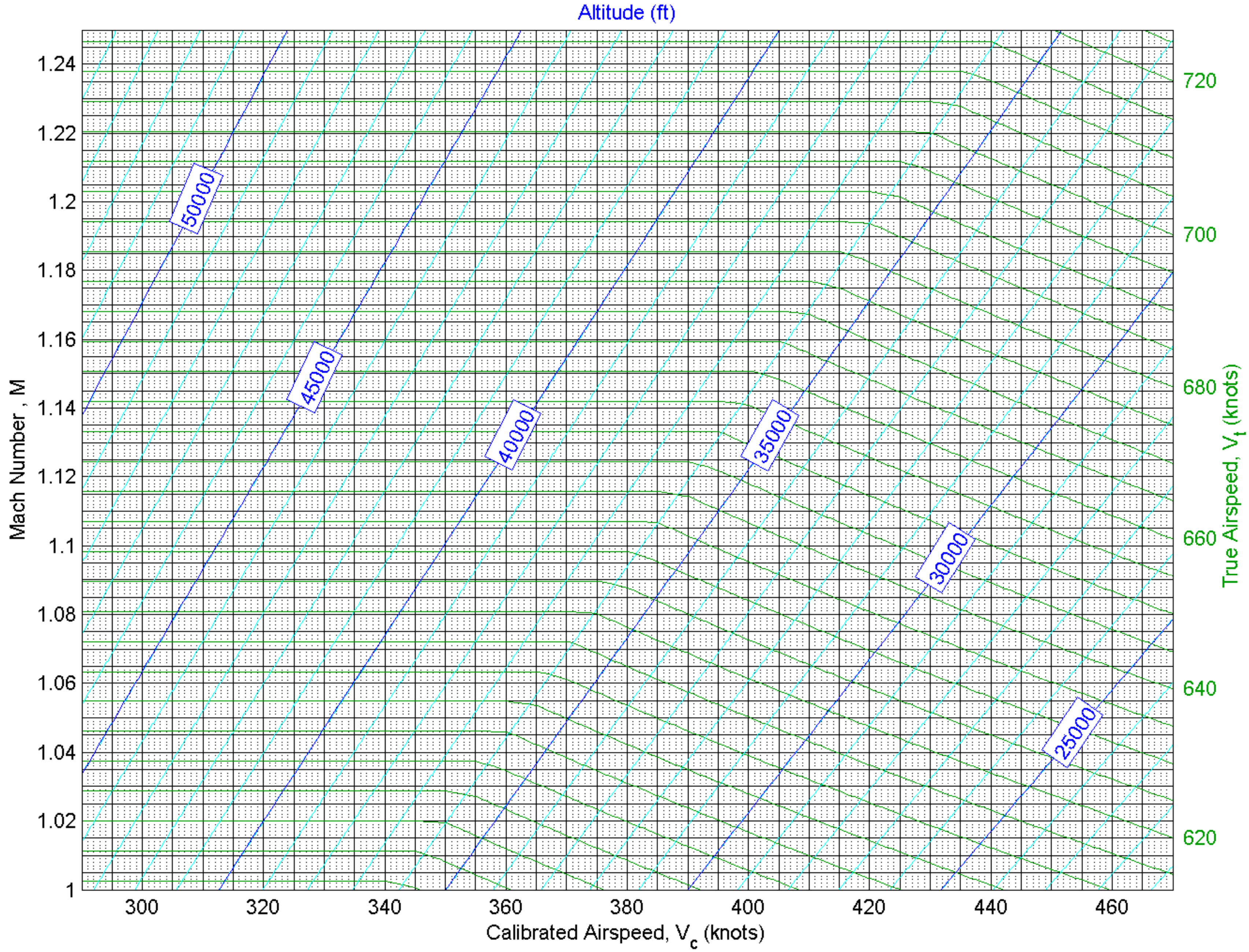

Altitude (ft)
5000
True Airspeed, V_t (knots)
400
420
440
460
480
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0.52
0.5
Mach Number , M
400
420
440
460
480
500
520
540
560
Calibrated Airspeed, V_c (knots)

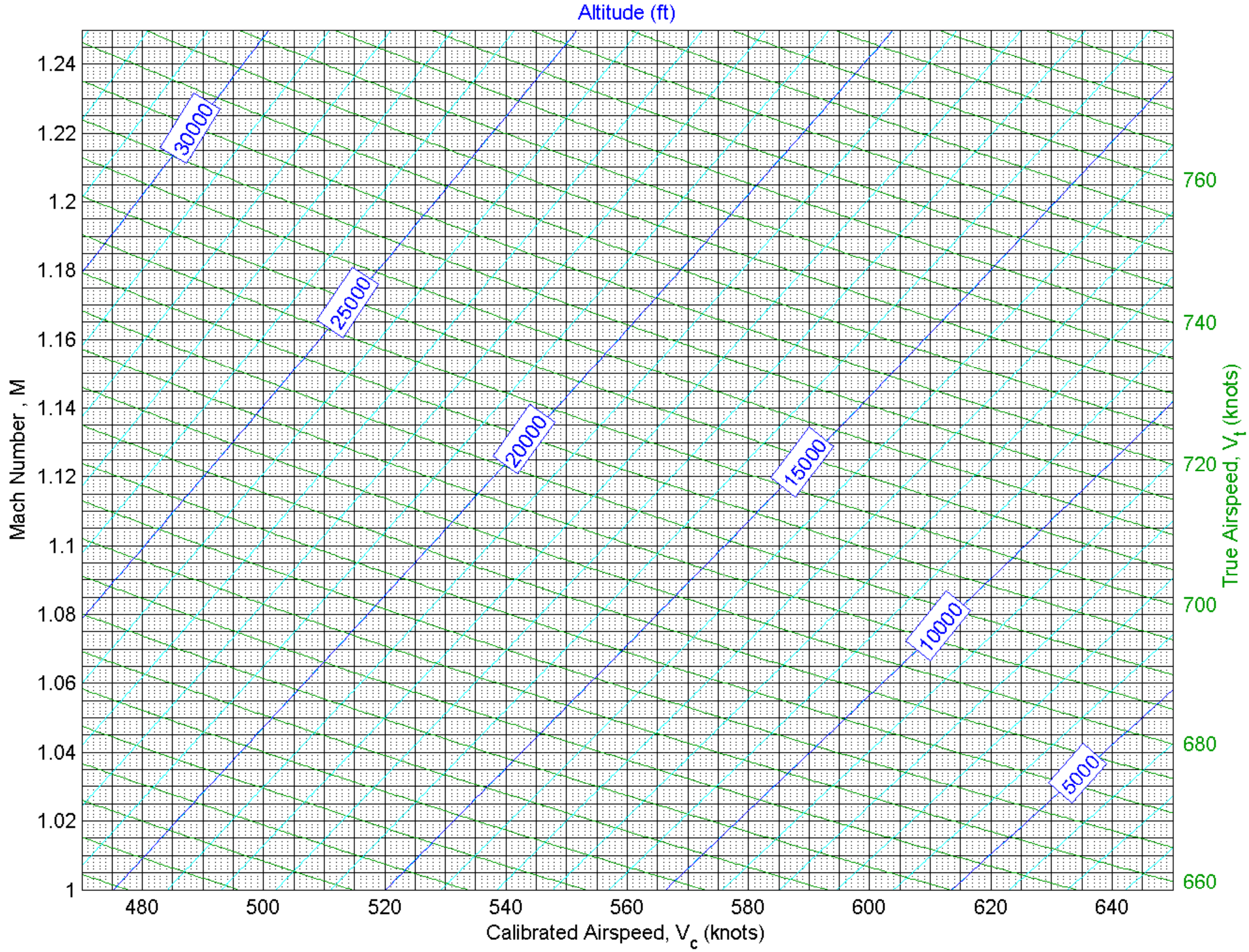

Altitude (ft)
80000
70000
60000
50000
40000
Mach Number , M
0.75
0.77
0.79
0.81
0.83
0.85
0.87
0.89
0.91
0.93
0.95
0.97
0.99
True Airspeed, V_t (knots)
440
460
480
500
520
540
560
Calibrated Airspeed, V_c (knots)
80
100
120
140
160
180
200
220
240
260

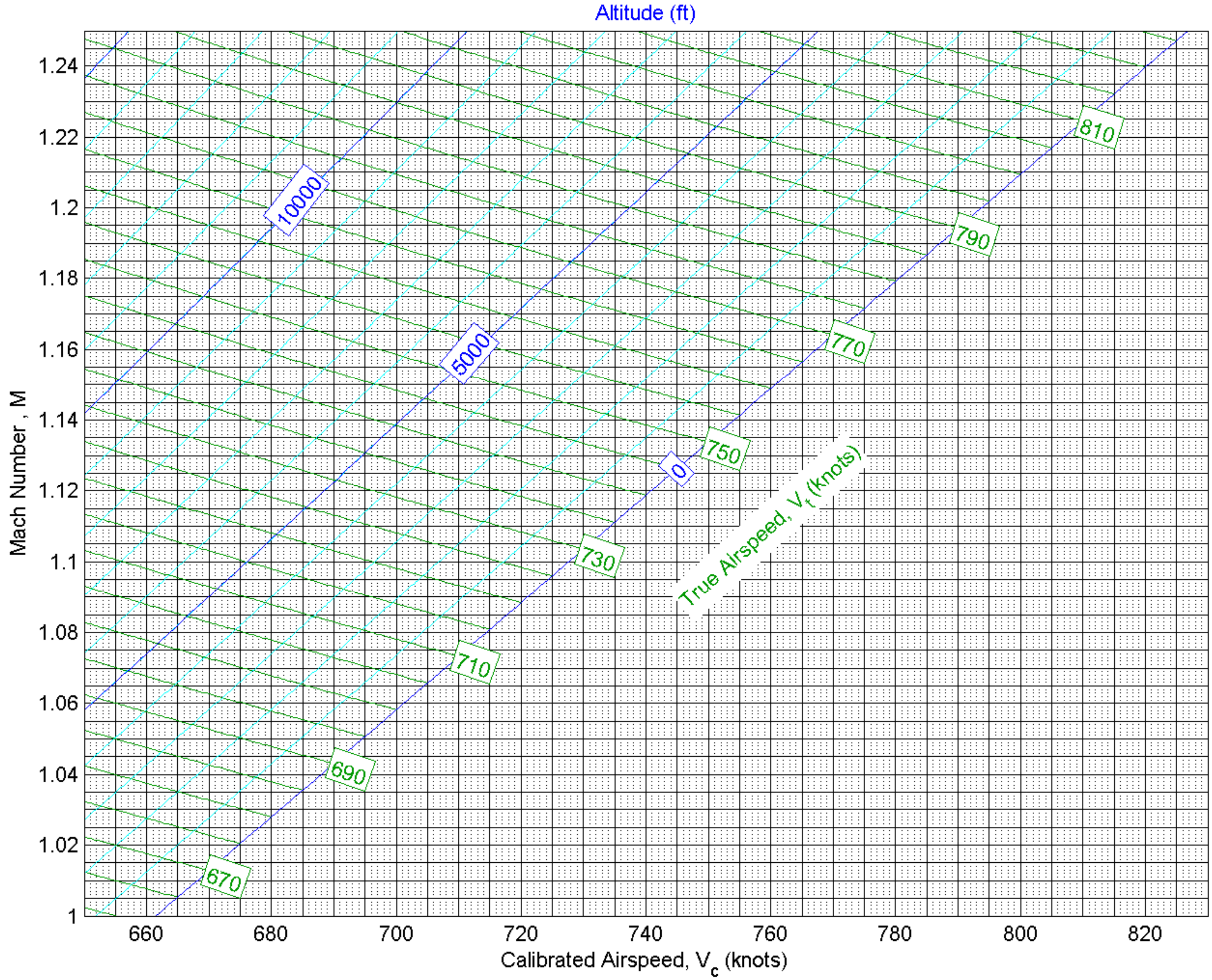

Altitude (ft)
Mach Number , M
0.99
0.97
0.95
0.93
0.91
0.89
0.87
0.85
0.83
0.81
0.79
0.77
0.75
260
280
300
320
340
360
380
400
420
440
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
600
580
560
540
520
500
45000
40000
35000
30000
25000
20000
15000
10000


Altitude (ft)
20000
15000
10000
5000
0
650
630
610
590
570
550
530
510
True Airspeed, V_t (knots)
Mach Number , M
0.99
0.97
0.95
0.93
0.91
0.89
0.87
0.85
0.83
0.81
0.79
0.77
0.75
440
460
480
500
520
540
560
580
600
620
640
660
Calibrated Airspeed, V_c (knots)

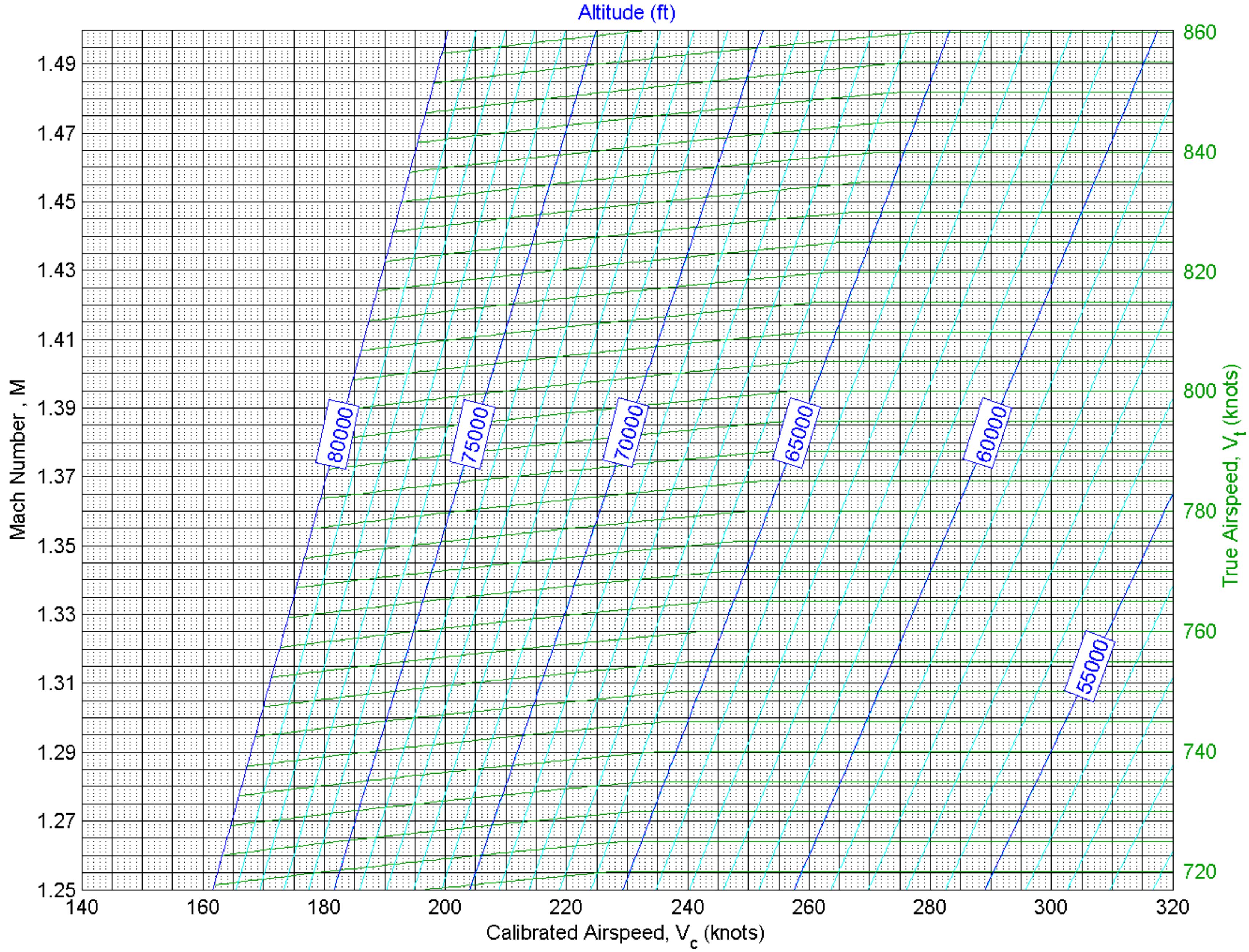

Altitude (ft)
80000
75000
70000
65000
60000
55000
50000
Mach Number , M
1
1.02
1.04
1.06
1.08
1.1
1.12
1.14
1.16
1.18
1.2
1.22
1.24
Calibrated Airspeed, V_c (knots)
120
140
160
180
200
220
240
260
280
True Airspeed, V_t (knots)
580
600
620
640
660
680
700


Altitude (ft)
50000
45000
40000
35000
30000
25000
Mach Number , M
1
1.02
1.04
1.06
1.08
1.1
1.12
1.14
1.16
1.18
1.2
1.22
1.24
300
320
340
360
380
400
420
440
460
Calibrated Airspeed, Vc (knots)
True Airspeed, Vt (knots)
620
640
660
680
700
720

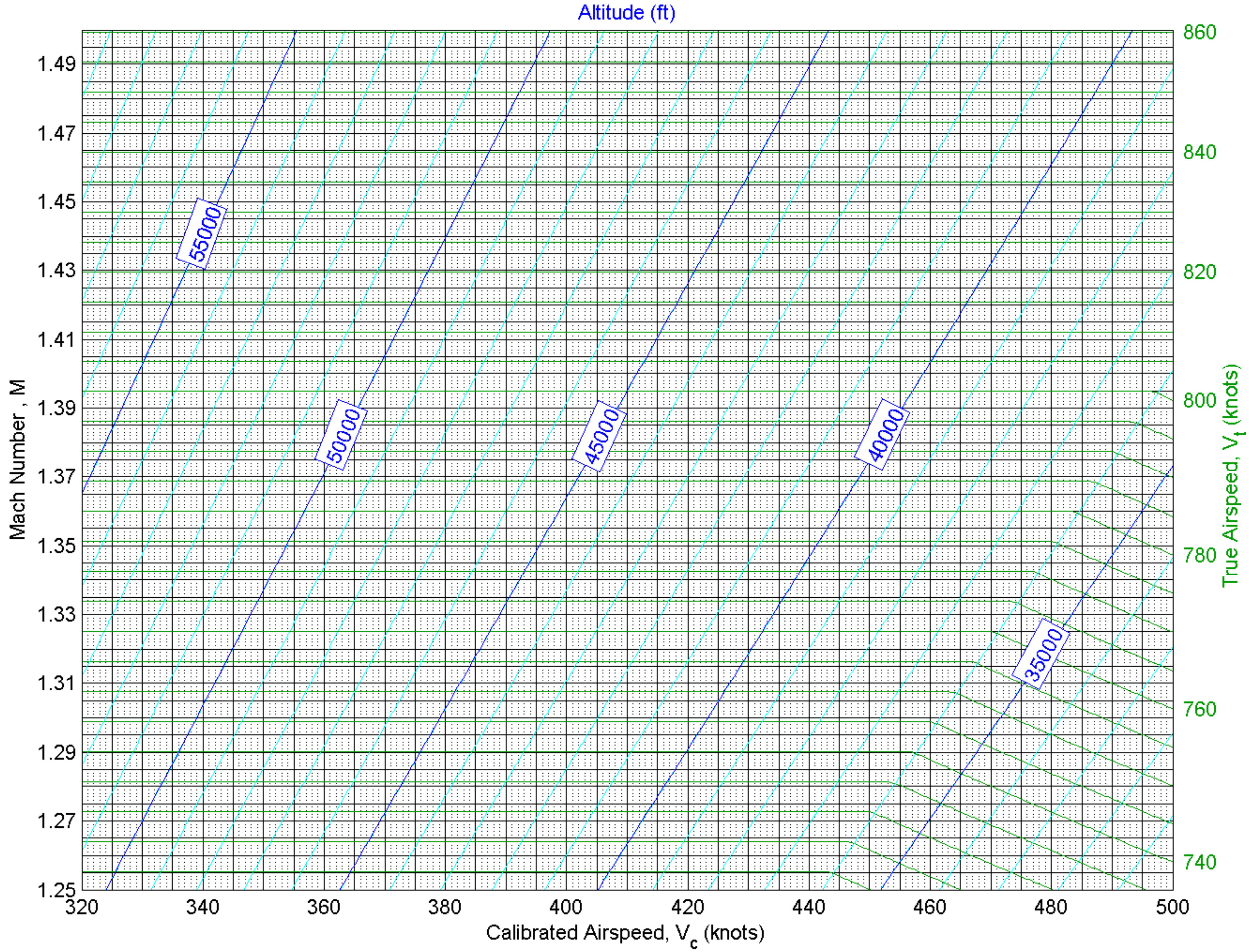

Altitude (ft)
30000
25000
20000
15000
10000
5000
Mach Number , M
1.24
1.22
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
True Airspeed, V_t (knots)
760
740
720
700
680
660
Calibrated Airspeed, V_c (knots)
480
500
520
540
560
580
600
620
640



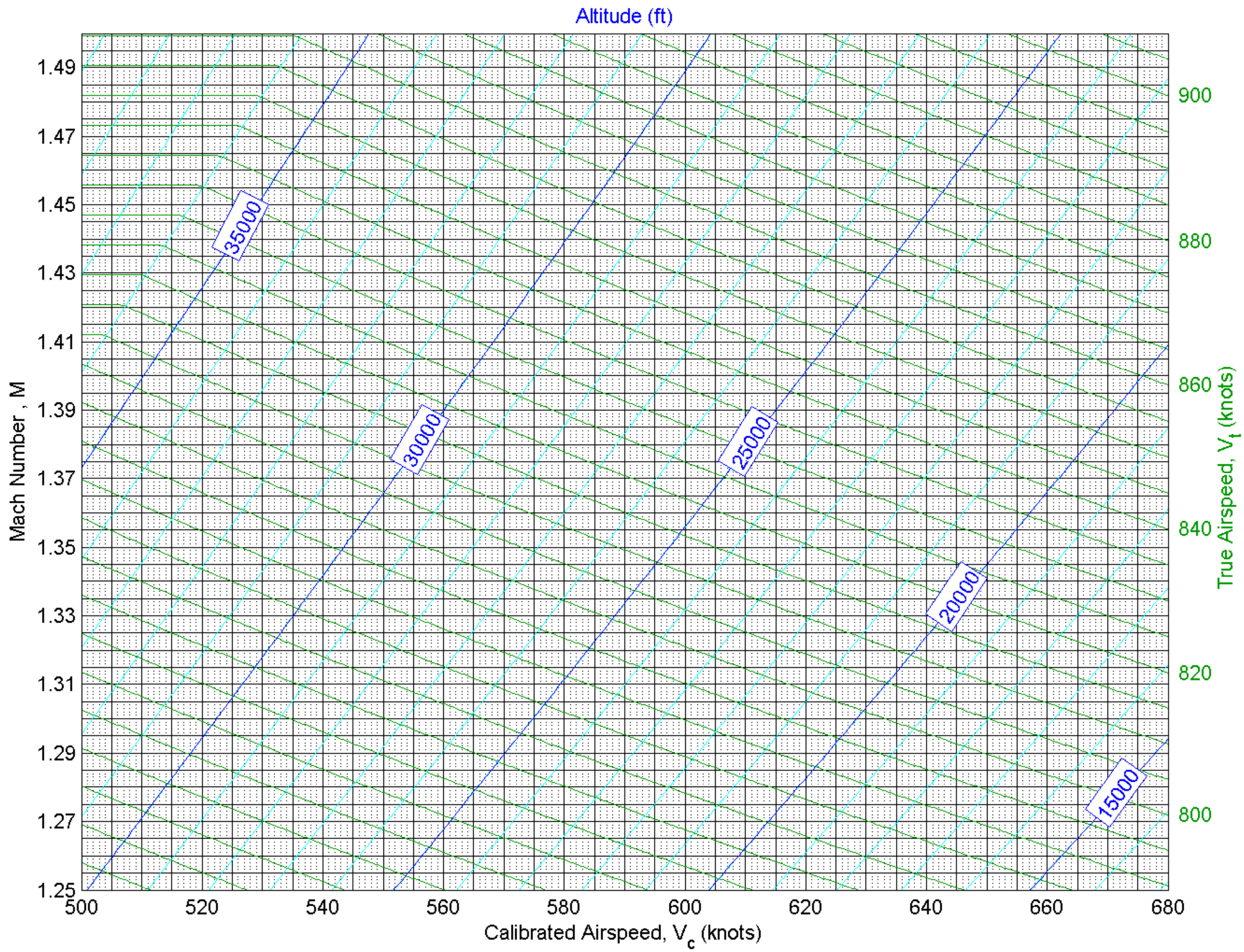
Altitude (ft)
10000
5000
0
670
690
710
730
750
770
790
810
True Airspeed, V_t (knots)
Mach Number, M
1.24
1.22
1.2
1.18
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
660
680
700
720
740
760
780
800
820
Calibrated Airspeed, V_c (knots)



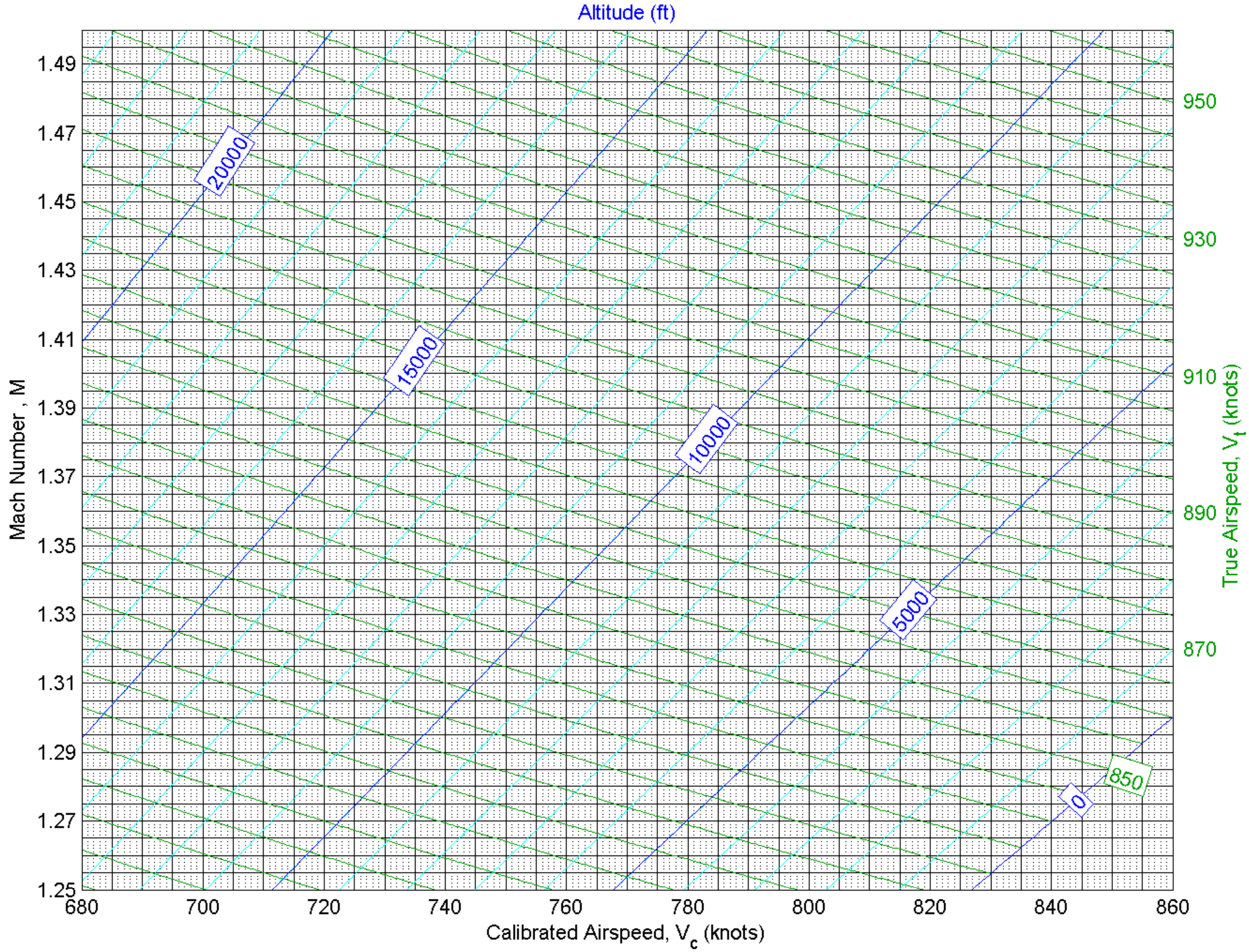
Altitude (ft)
80000
75000
70000
65000
60000
55000
Mach Number, M
1.25
1.27
1.29
1.31
1.33
1.35
1.37
1.39
1.41
1.43
1.45
1.47
1.49
True Airspeed, V_t (knots)
720
740
760
780
800
820
840
860
Calibrated Airspeed, V_c (knots)
140
160
180
200
220
240
260
280
300
320



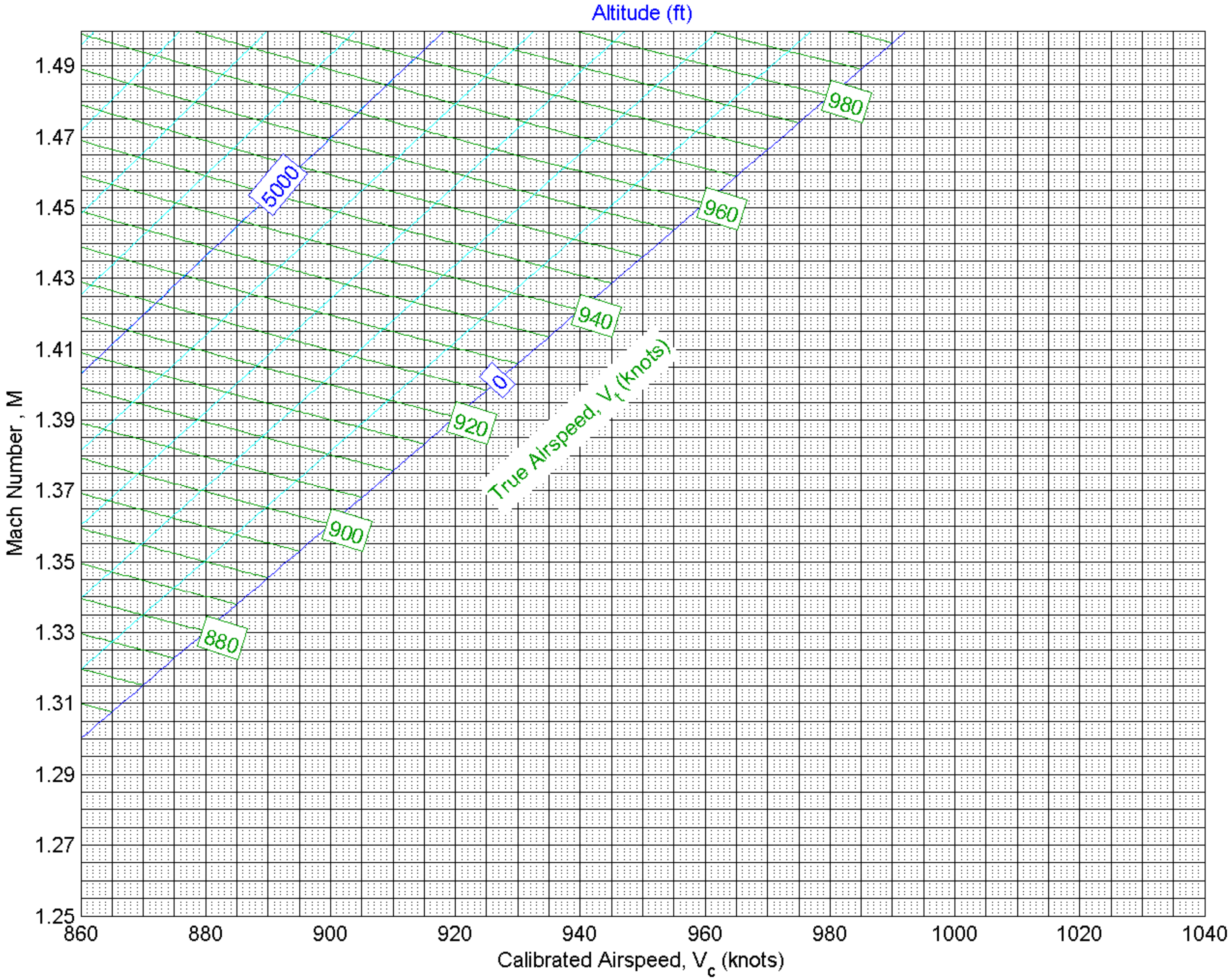
Altitude (ft)
55000
50000
45000
40000
35000
Mach Number , M
1.49
1.47
1.45
1.43
1.41
1.39
1.37
1.35
1.33
1.31
1.29
1.27
1.25
True Airspeed, V_t (knots)
860
840
820
800
780
760
740
Calibrated Airspeed, V_c (knots)
320
340
360
380
400
420
440
460
480
500

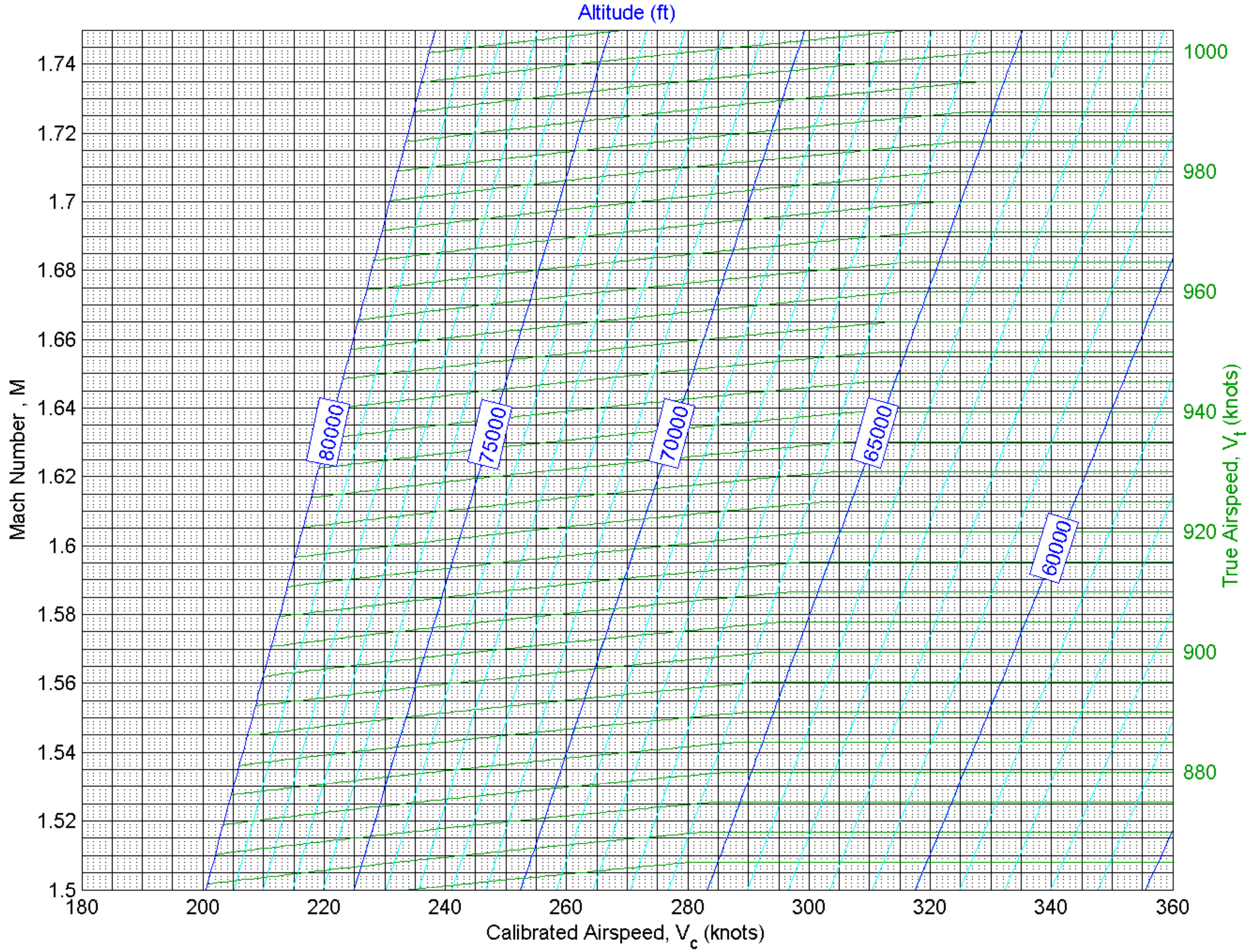


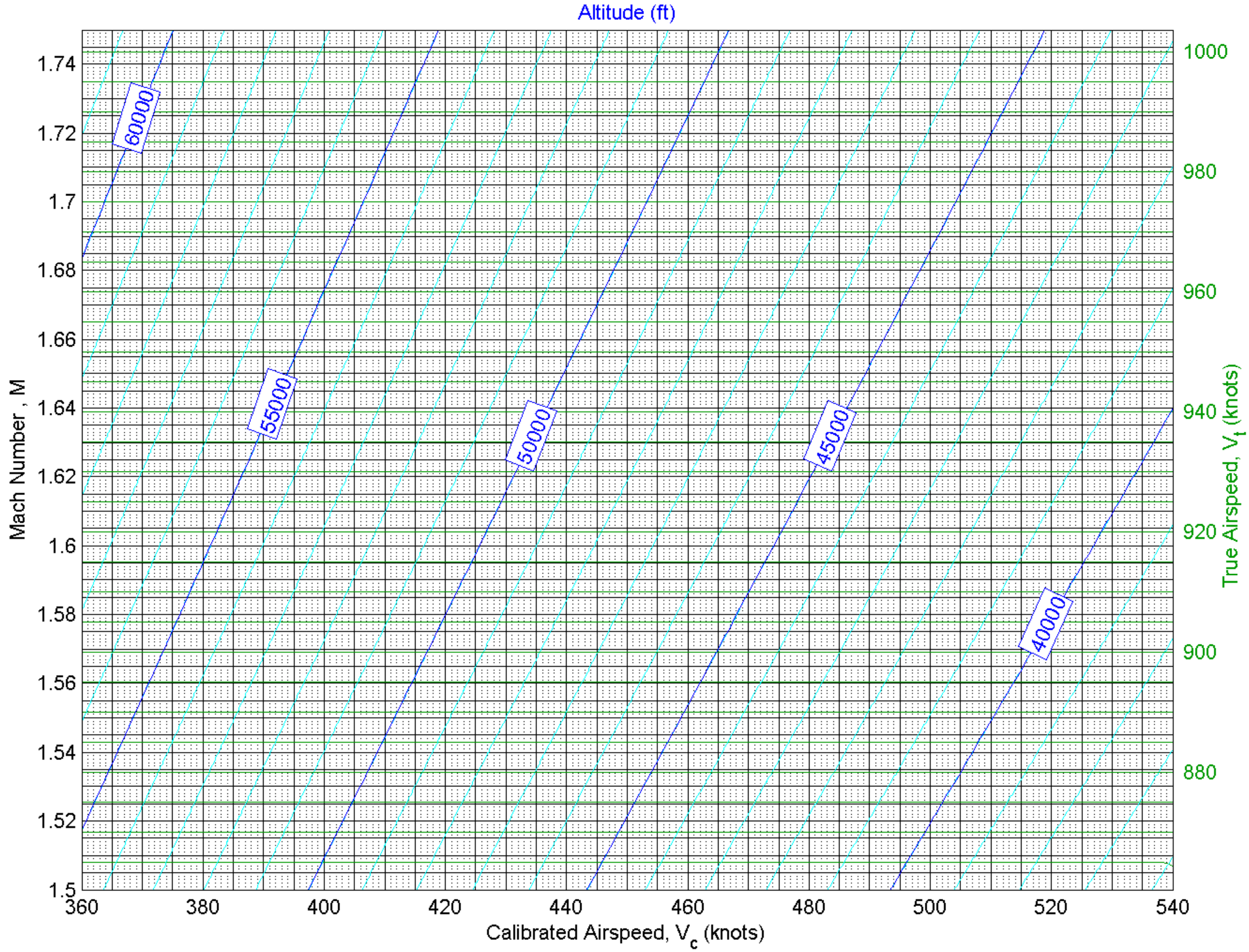
Altitude (ft)
35000
30000
25000
20000
15000
Mach Number , M
1.25
1.27
1.29
1.31
1.33
1.35
1.37
1.39
1.41
1.43
1.45
1.47
1.49
Calibrated Airspeed, V_c (knots)
500
520
540
560
580
600
620
640
660
680
True Airspeed, V_t (knots)
800
820
840
860
880
900

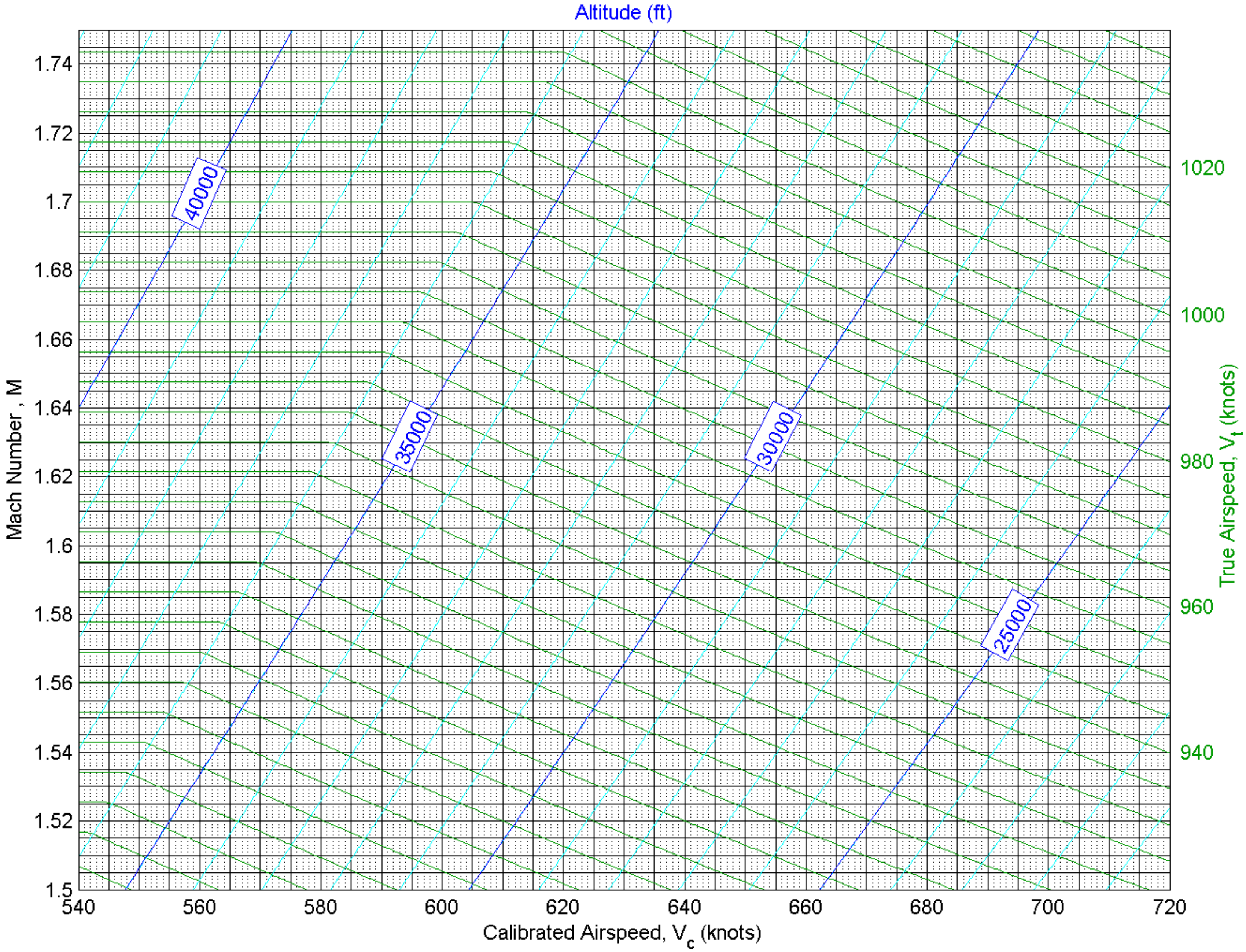


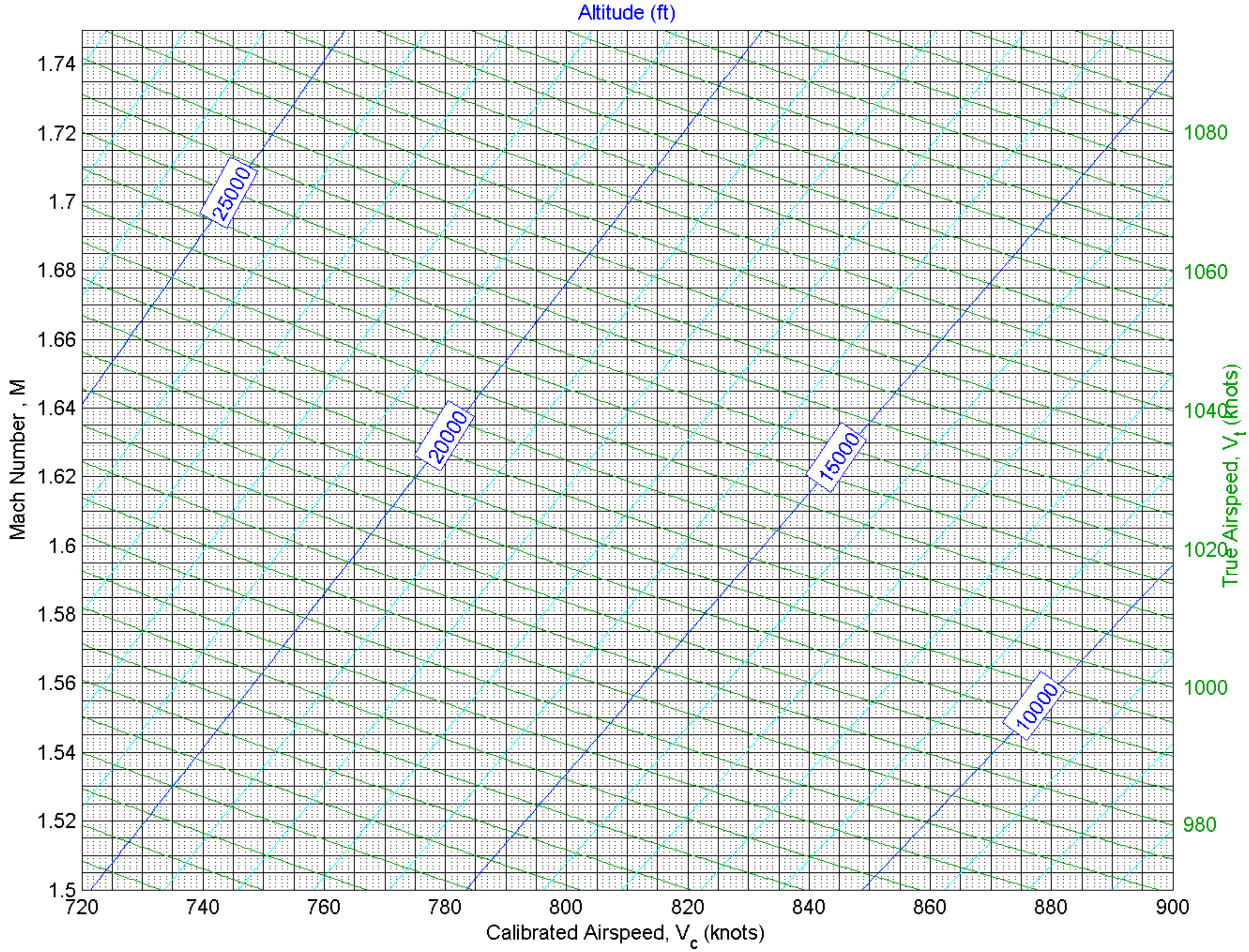
Altitude (ft)
20000
15000
10000
5000
0
850
Mach Number , M
1.49
1.47
1.45
1.43
1.41
1.39
1.37
1.35
1.33
1.31
1.29
1.27
1.25
950
930
910
890
870
True Airspeed, V_t (knots)
680
700
720
740
760
780
800
820
840
860
Calibrated Airspeed, V_c (knots)

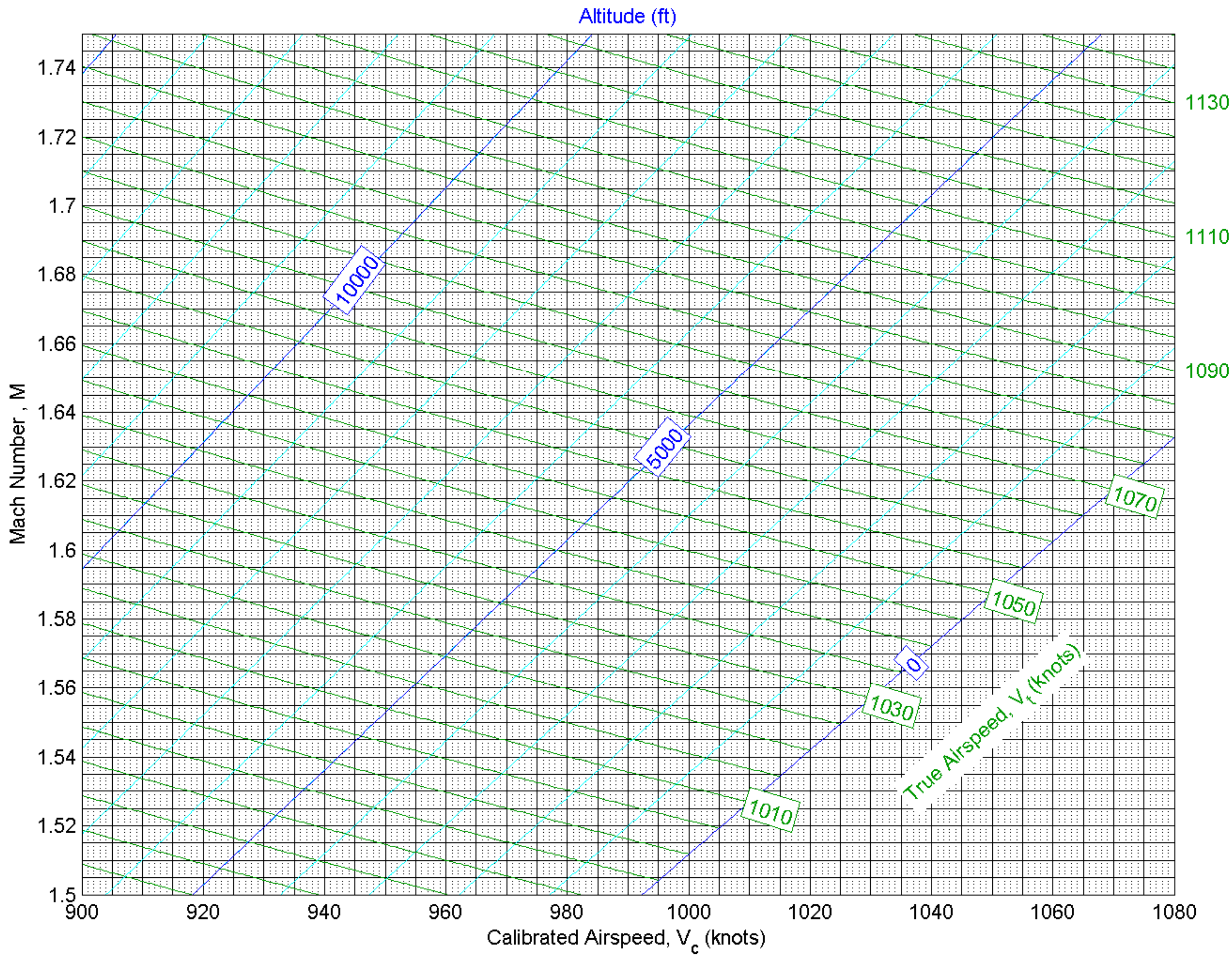

Altitude (ft)
5000
0
980
960
940
920
900
880
True Airspeed, V_t (knots)
Mach Number , M
1.49
1.47
1.45
1.43
1.41
1.39
1.37
1.35
1.33
1.31
1.29
1.27
1.25
860
880
900
920
940
960
980
1000
1020
1040
Calibrated Airspeed, V_c (knots)

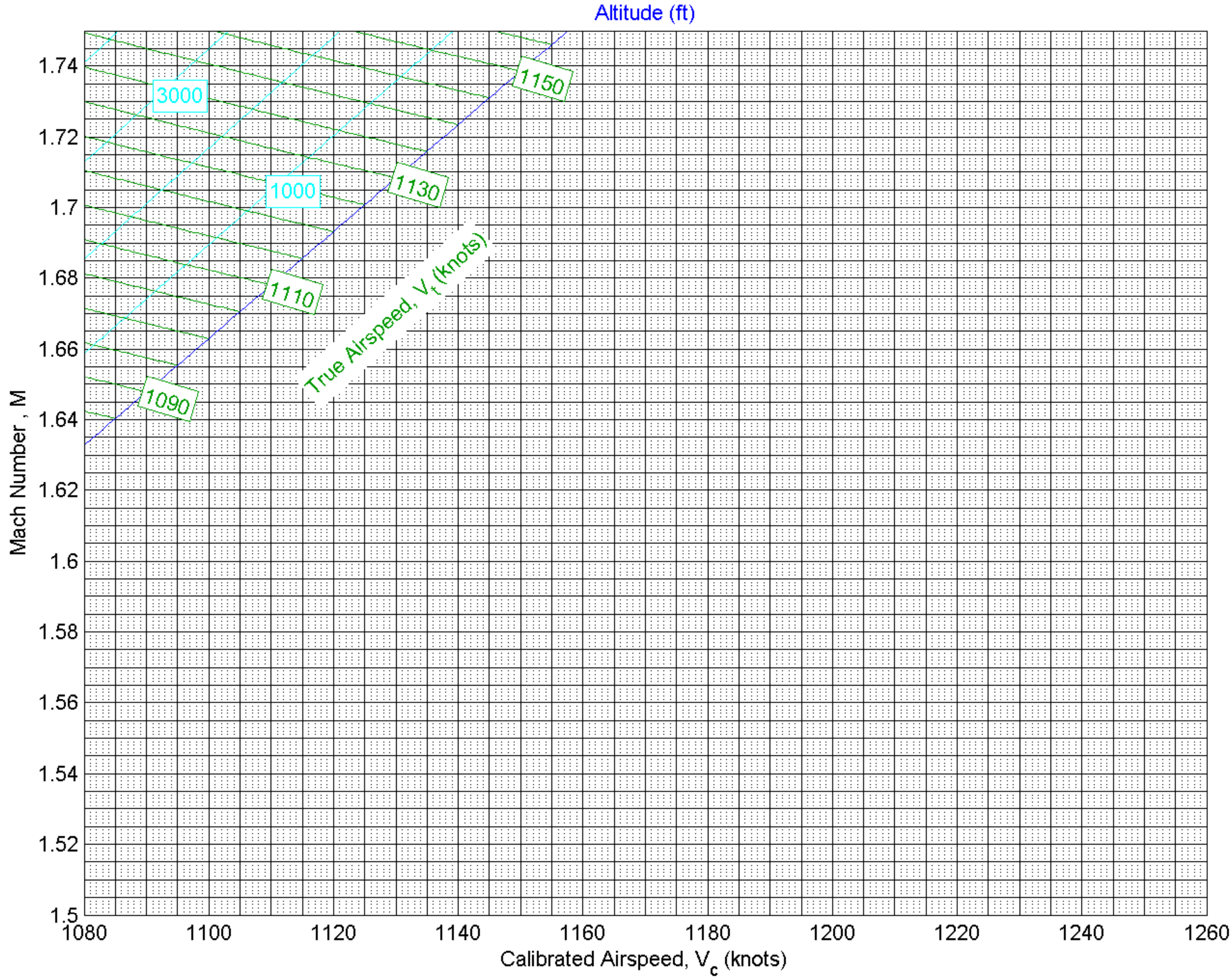

Altitude (ft)
Mach Number , M
True Airspeed, V_t (knots)
Calibrated Airspeed, V_c (knots)
80000
75000
70000
65000
60000
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
180
200
220
240
260
280
300
320
340
360
1000
980
960
940
920
900
880


Altitude (ft)
60000
55000
50000
45000
40000
Mach Number , M
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
True Airspeed, V_t (knots)
1000
980
960
940
920
900
880
360
380
400
420
440
460
480
500
520
540
Calibrated Airspeed, V_c (knots)

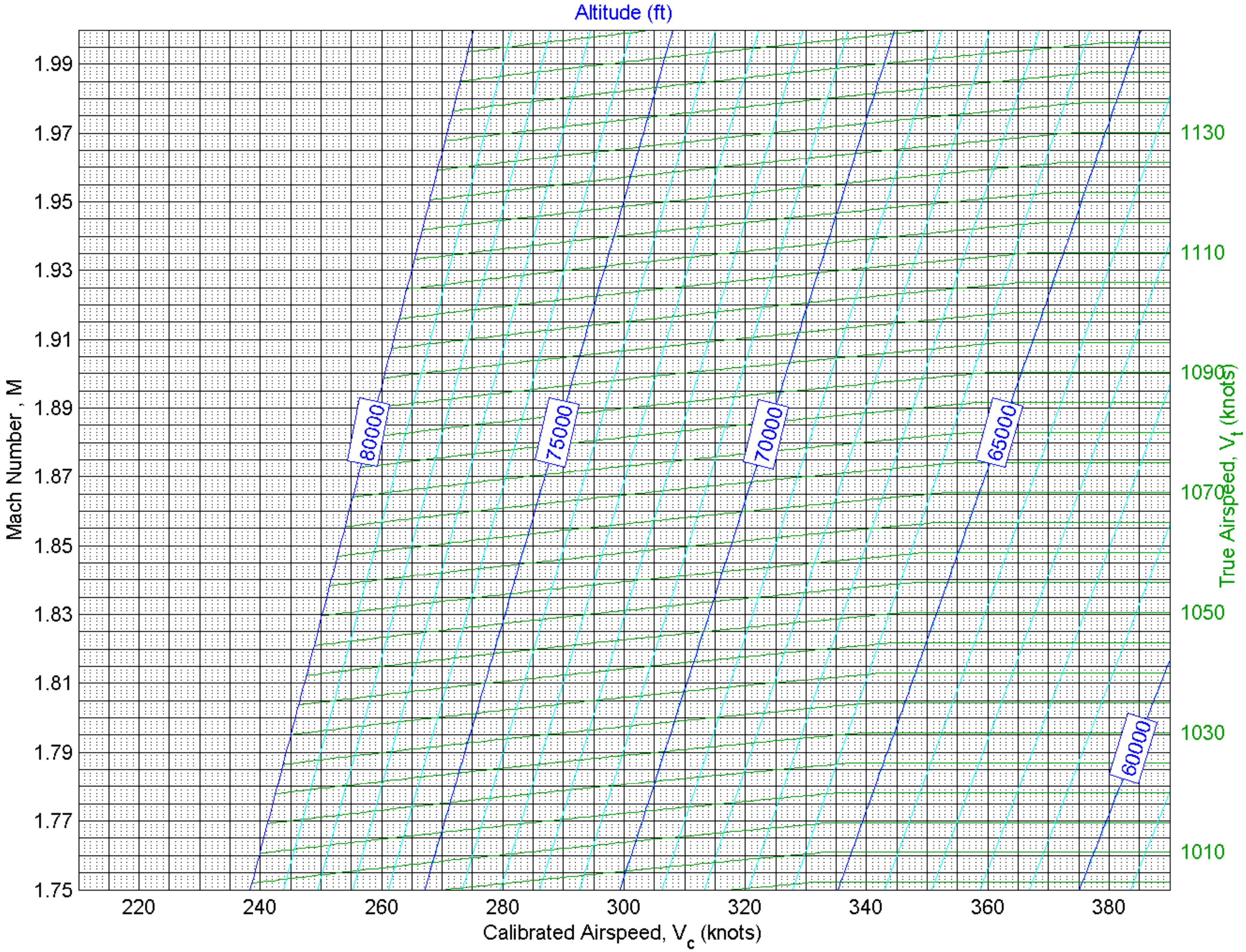

Altitude (ft)
40000
35000
30000
25000
Mach Number , M
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
Calibrated Airspeed, V_c (knots)
540
560
580
600
620
640
660
680
700
720
True Airspeed, V_t (knots)
1020
1000
980
960
940

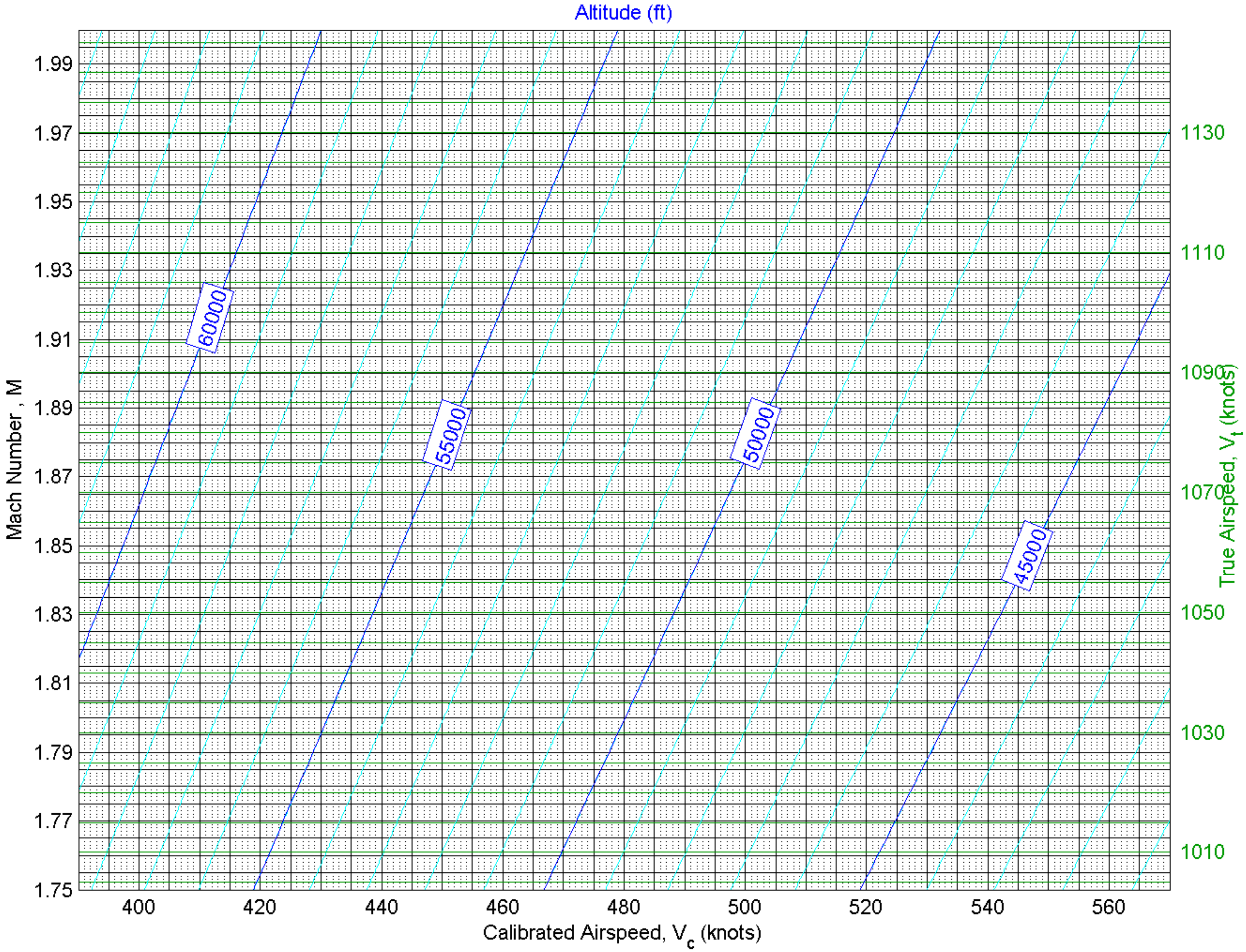

Altitude (ft)
25000
20000
15000
10000
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
Mach Number , M
720
740
760
780
800
820
840
860
880
900
Calibrated Airspeed, V_c (knots)
1080
1060
1040
1020
1000
980
True Airspeed, V_t (knots)

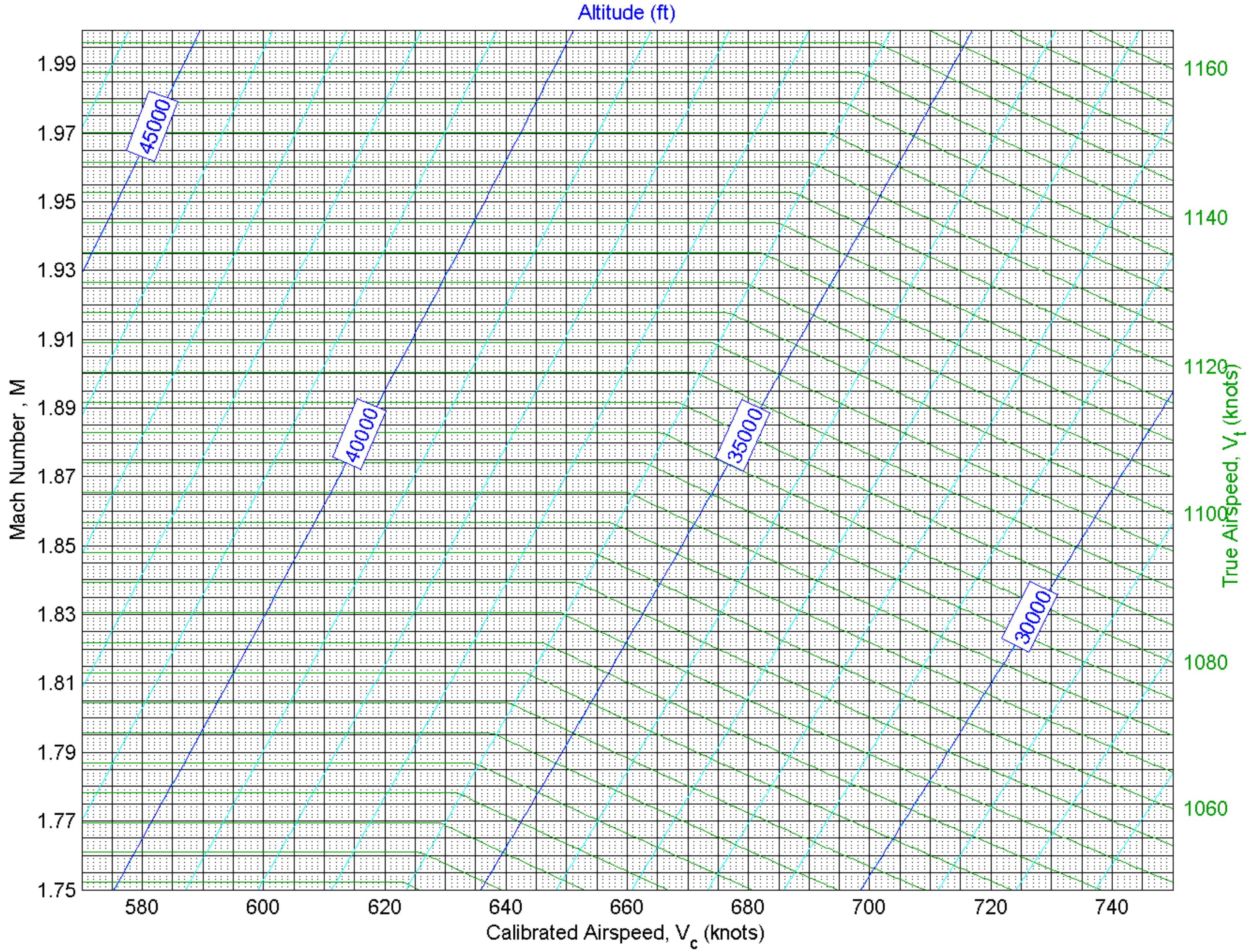

Altitude (ft)
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
Mach Number , M
900
920
940
960
980
1000
1020
1040
1060
1080
Calibrated Airspeed, V_c (knots)
10000
5000
0
1130
1110
1090
1070
1050
1030
1010
True Airspeed, V_t (knots)



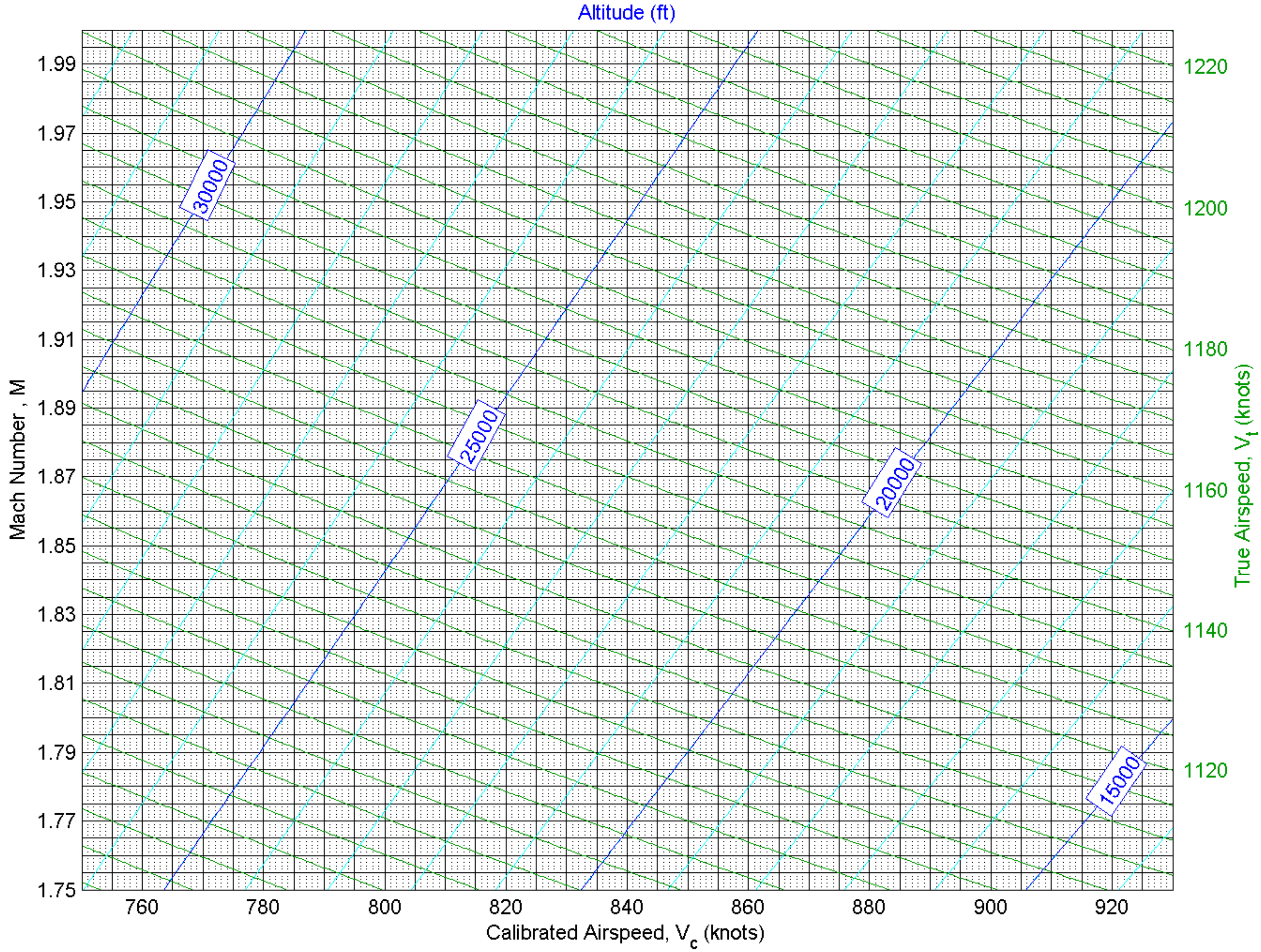
Altitude (ft)
3000
1000
1150
1130
1110
1090
True Airspeed, V_t (knots)
Mach Number , M
1.74
1.72
1.7
1.68
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
1080
1100
1120
1140
1160
1180
1200
1220
1240
1260
Calibrated Airspeed, V_c (knots)


Altitude (ft)
80000
75000
70000
65000
60000
Mach Number , M
1.99
1.97
1.95
1.93
1.91
1.89
1.87
1.85
1.83
1.81
1.79
1.77
1.75
220
240
260
280
300
320
340
360
380
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1130
1110
1090
1070
1050
1030
1010

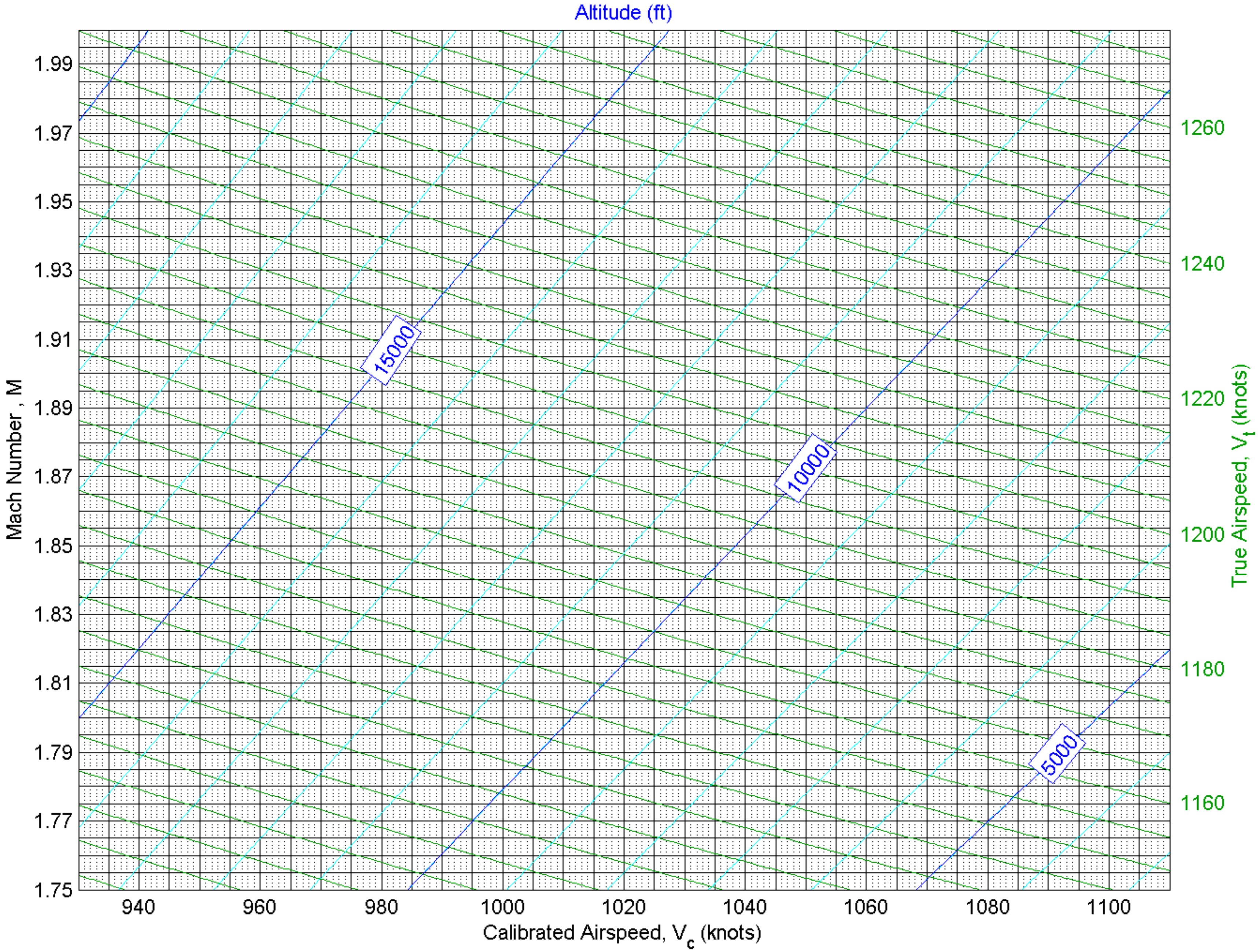

Altitude (ft)
60000
55000
50000
45000
Mach Number , M
1.99
1.97
1.95
1.93
1.91
1.89
1.87
1.85
1.83
1.81
1.79
1.77
1.75
400
420
440
460
480
500
520
540
560
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1130
1110
1090
1070
1050
1030
1010



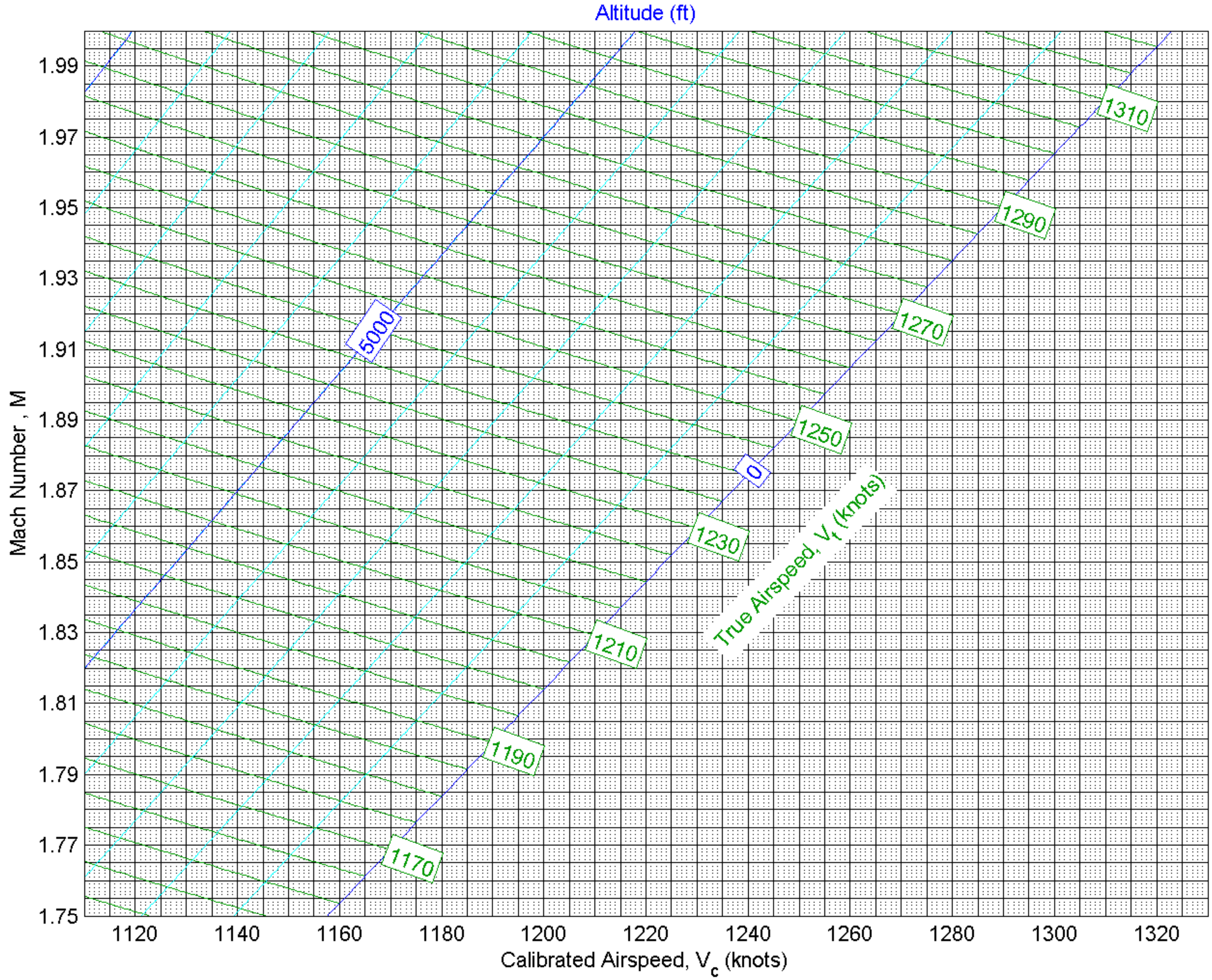
Altitude (ft)
45000
40000
35000
30000
Mach Number , M
1.99
1.97
1.95
1.93
1.91
1.89
1.87
1.85
1.83
1.81
1.79
1.77
1.75
580
600
620
640
660
680
700
720
740
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1160
1140
1120
1100
1080
1060



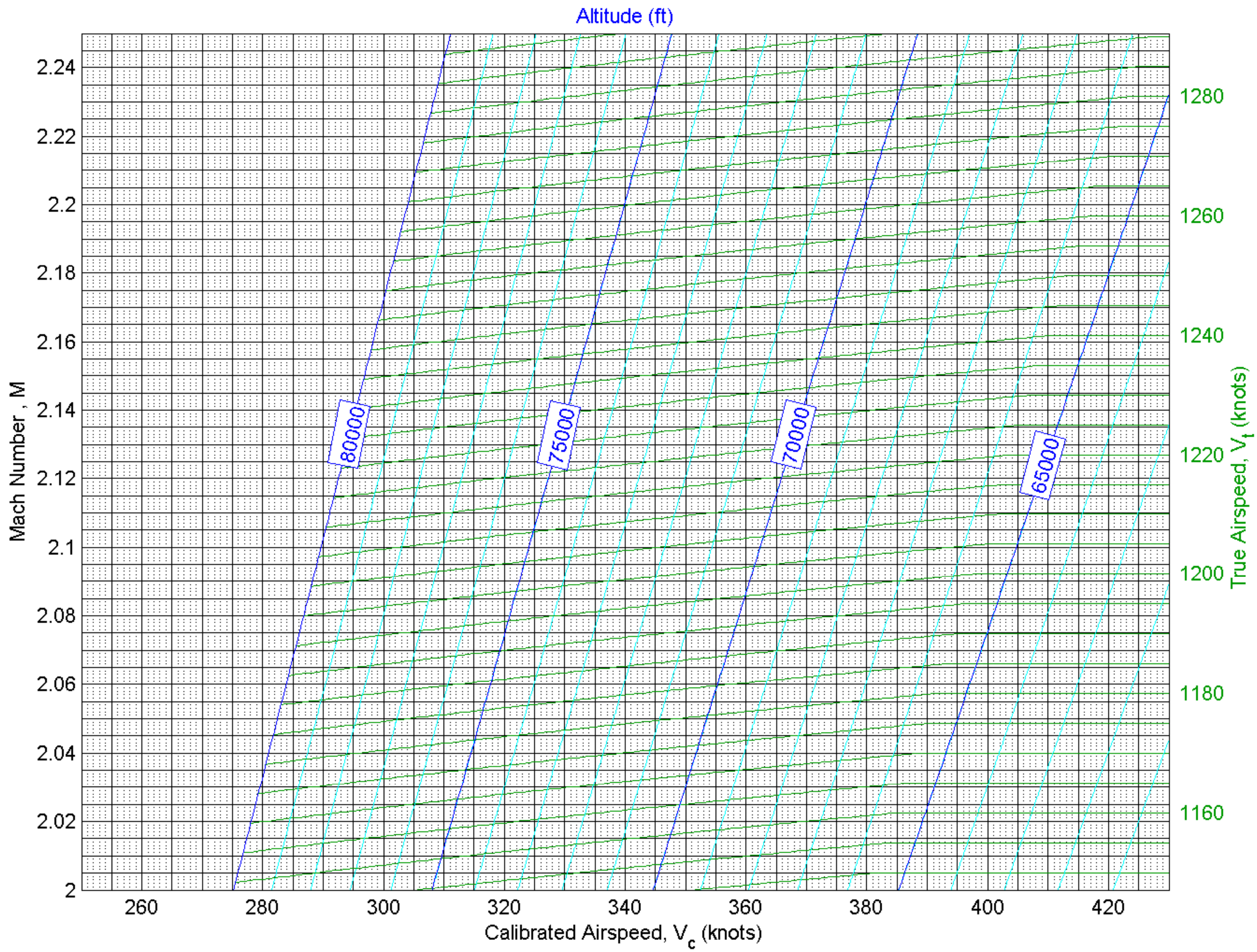
Altitude (ft)
30000
25000
20000
15000
Mach Number , M
1.99
1.97
1.95
1.93
1.91
1.89
1.87
1.85
1.83
1.81
1.79
1.77
1.75
True Airspeed, V_t (knots)
1220
1200
1180
1160
1140
1120
Calibrated Airspeed, V_c (knots)
760
780
800
820
840
860
880
900
920

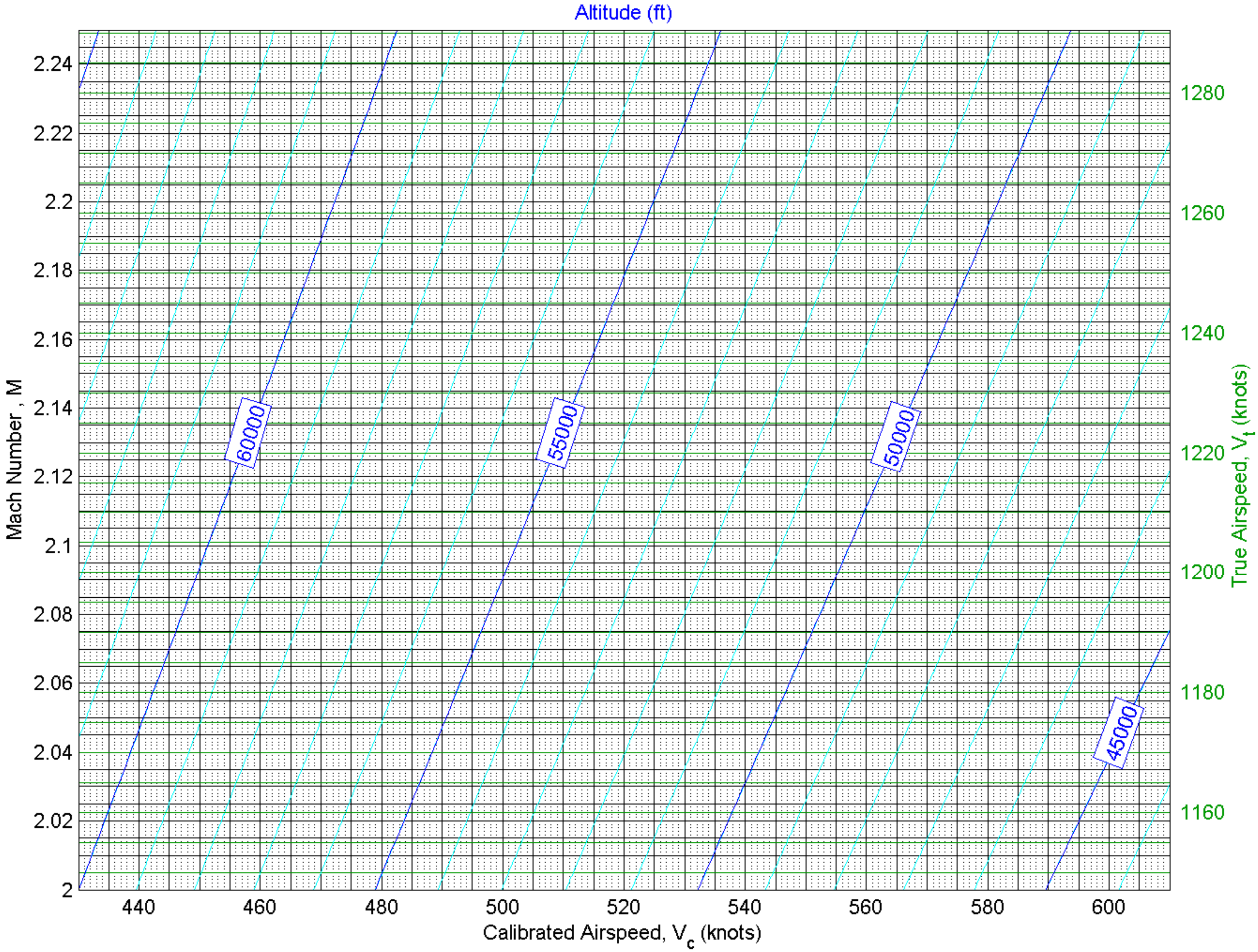


Altitude (ft)
15000
10000
5000
1.99
1.97
1.95
1.93
1.91
1.89
1.87
1.85
1.83
1.81
1.79
1.77
1.75
Mach Number , M
1260
1240
1220
1200
1180
1160
True Airspeed, V_t (knots)
940
960
980
1000
1020
1040
1060
1080
1100
Calibrated Airspeed, V_c (knots)

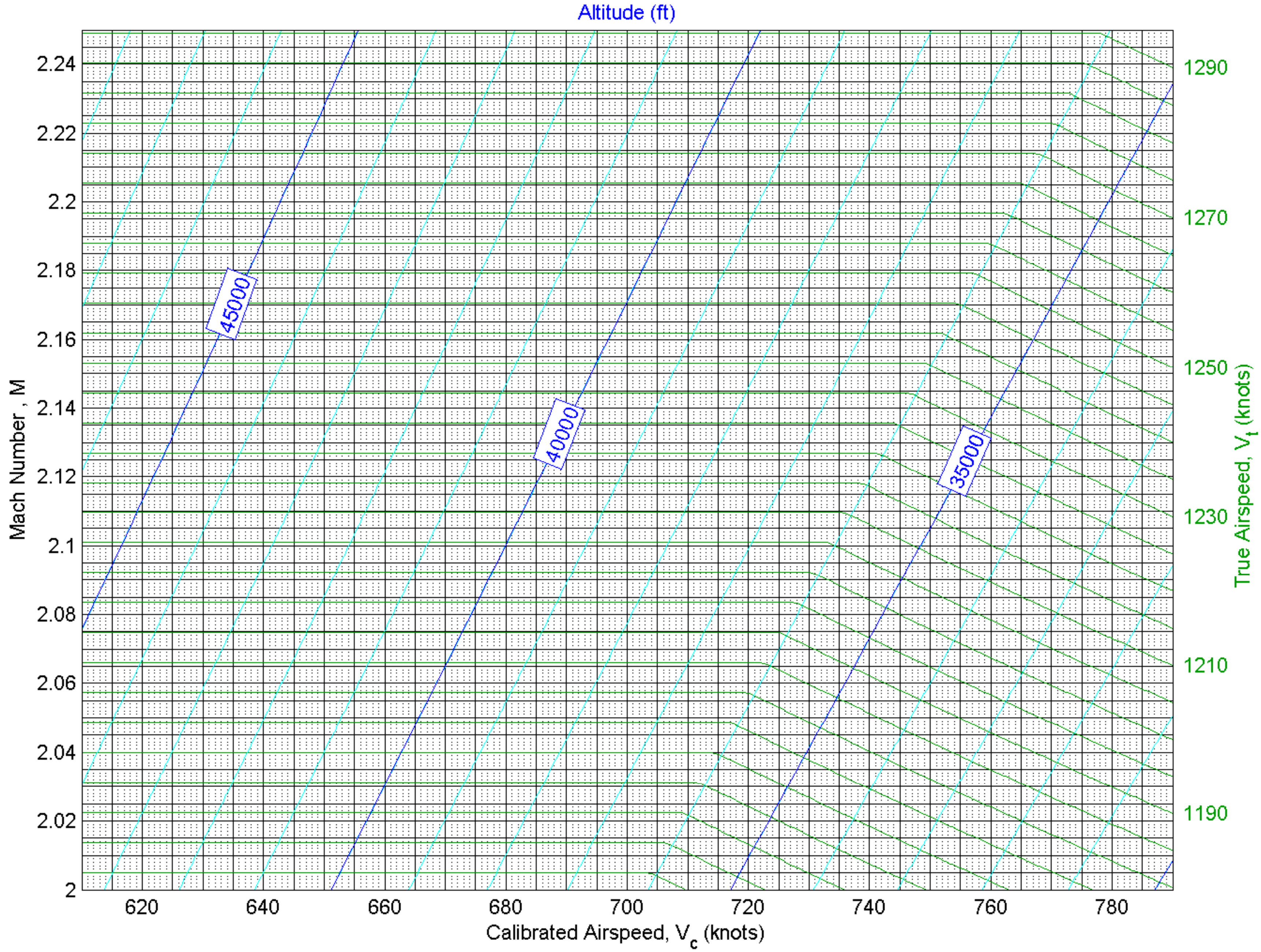


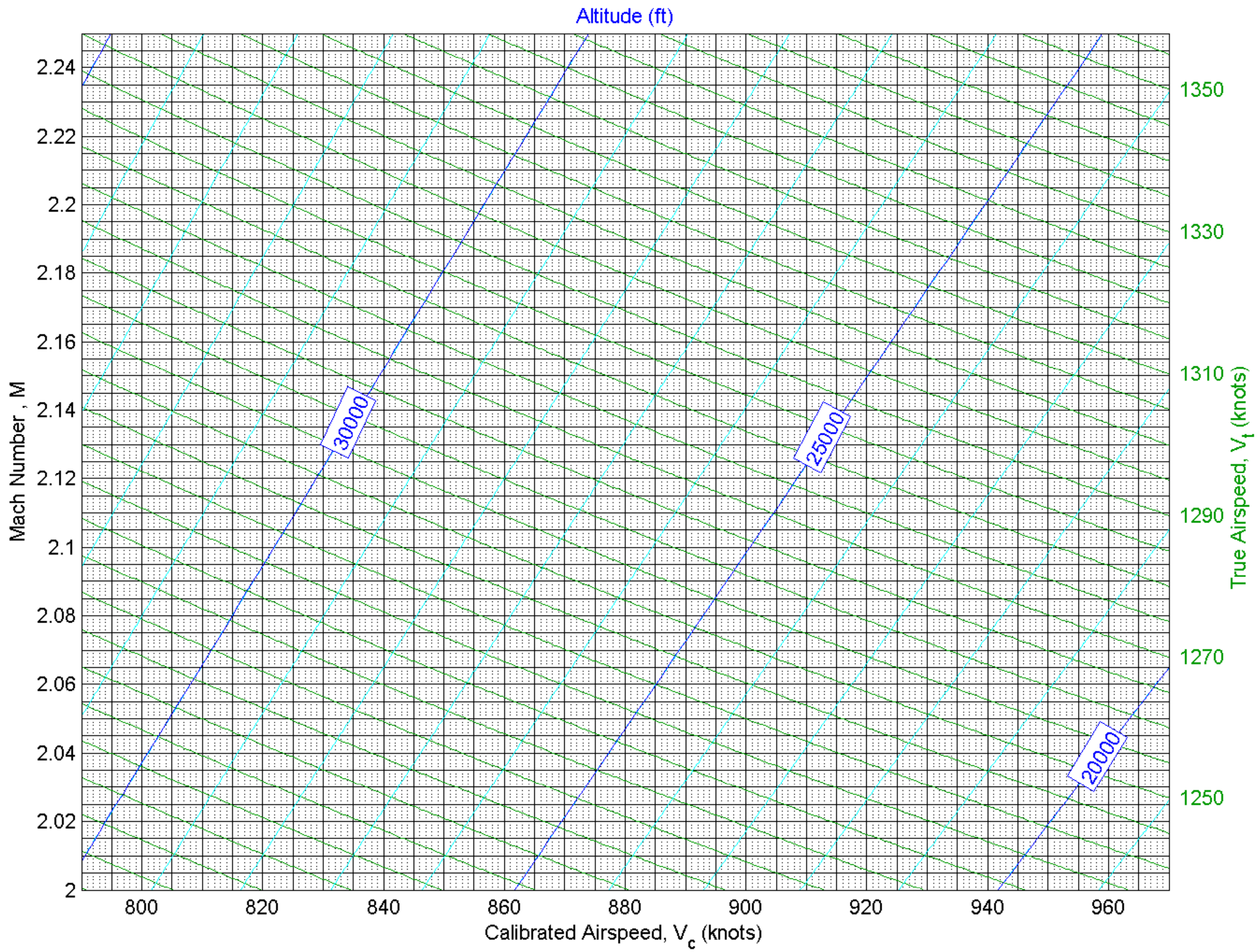
Altitude (ft)
Mach Number , M
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1.75
1.77
1.79
1.81
1.83
1.85
1.87
1.89
1.91
1.93
1.95
1.97
1.99
1120
1140
1160
1180
1200
1220
1240
1260
1280
1300
1320
5000
0
1170
1190
1210
1230
1250
1270
1290
1310


Altitude (ft)
80000
75000
70000
65000
Mach Number , M
2.24
2.22
2.2
2.18
2.16
2.14
2.12
2.1
2.08
2.06
2.04
2.02
2
Calibrated Airspeed, V_c (knots)
260
280
300
320
340
360
380
400
420
True Airspeed, V_t (knots)
1280
1260
1240
1220
1200
1180
1160

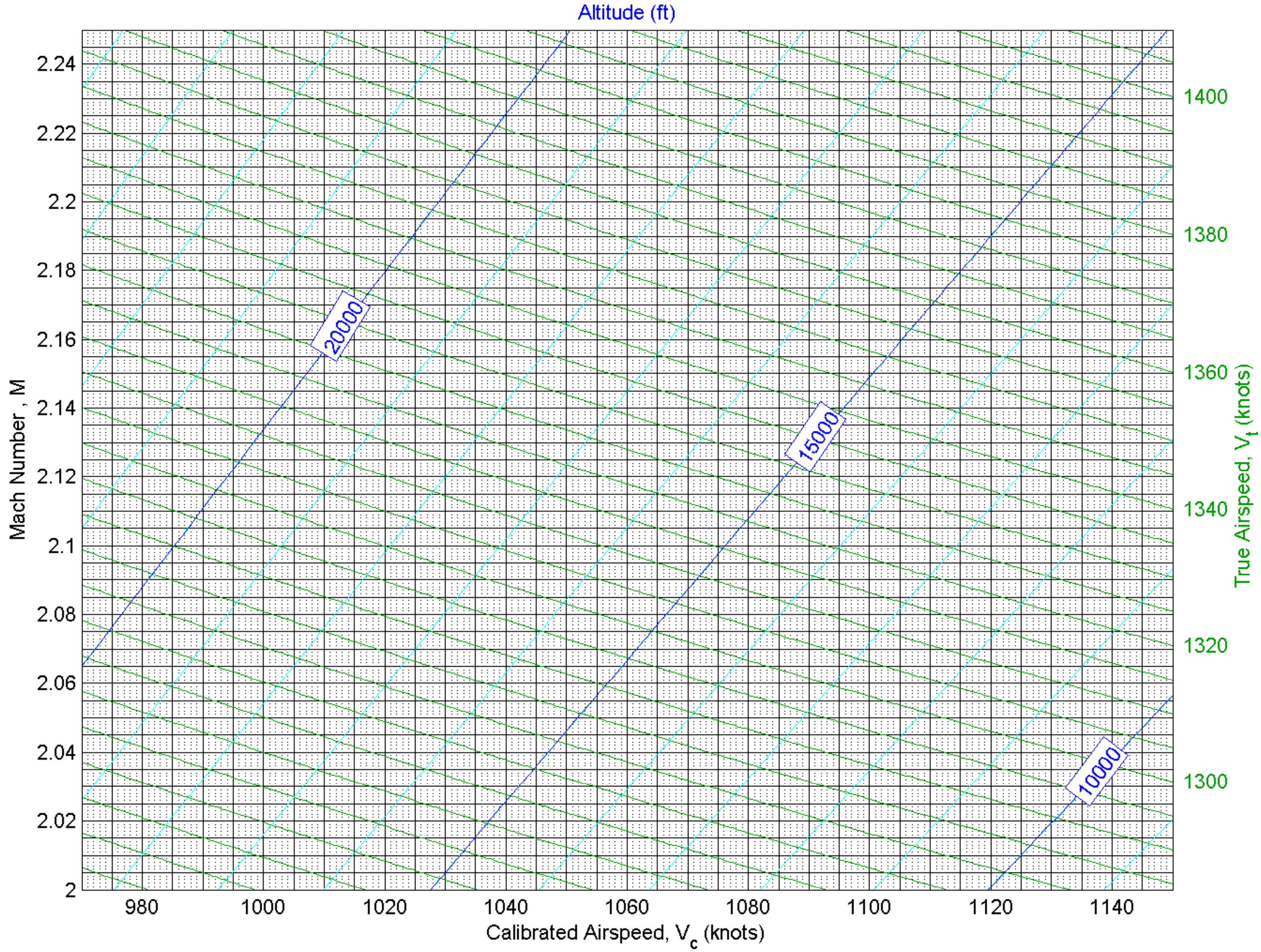


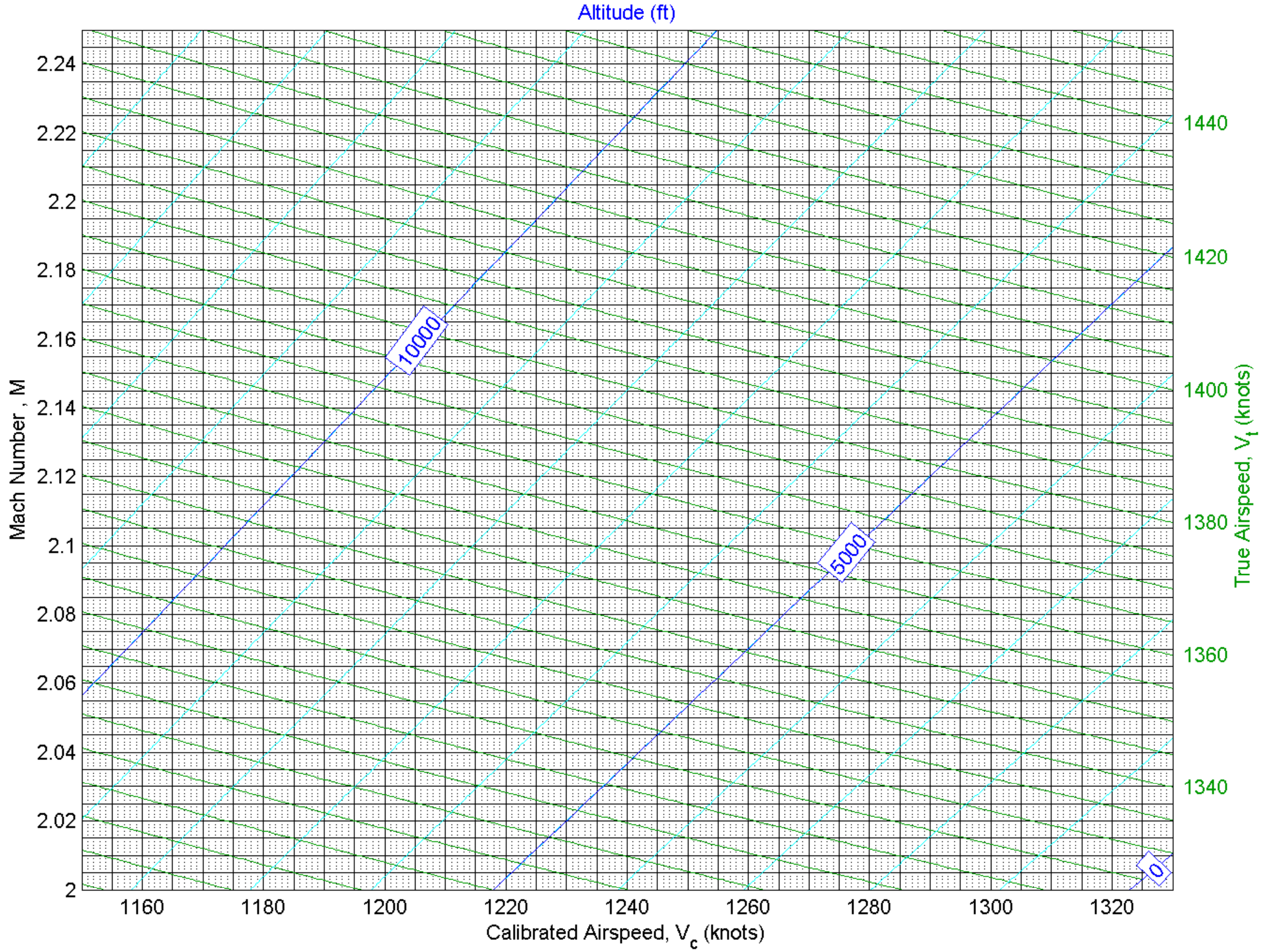
Altitude (ft)
Mach Number, M
2.24
2.22
2.2
2.18
2.16
2.14
2.12
2.1
2.08
2.06
2.04
2.02
2
440
460
480
500
520
540
560
580
600
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1280
1260
1240
1220
1200
1180
1160
60000
55000
50000
45000


Altitude (ft)
45000
40000
35000
Mach Number , M
2.24
2.22
2.2
2.18
2.16
2.14
2.12
2.1
2.08
2.06
2.04
2.02
2
620
640
660
680
700
720
740
760
780
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1290
1270
1250
1230
1210
1190

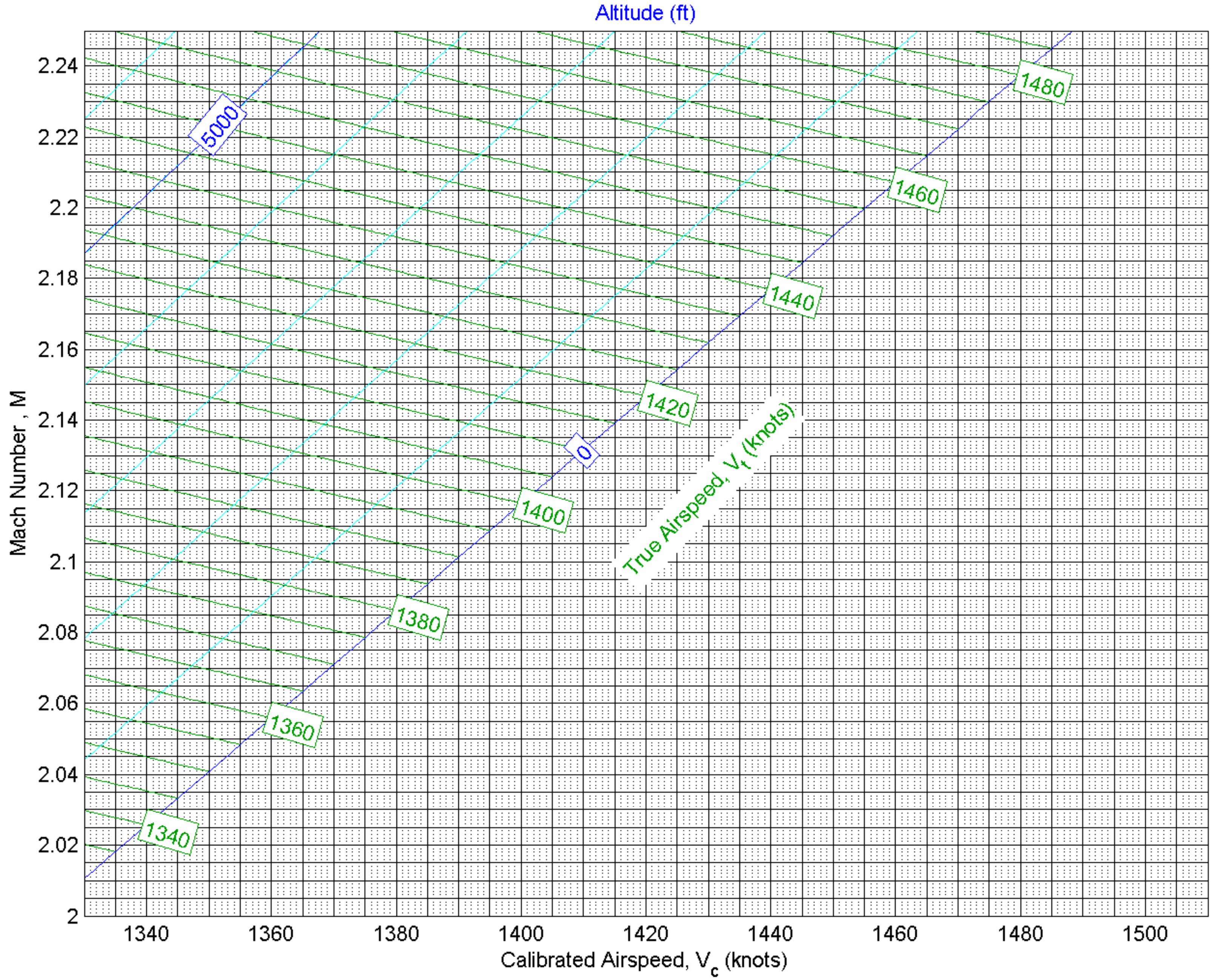


Altitude (ft)
30000
25000
20000
Mach Number , M
2
2.02
2.04
2.06
2.08
2.1
2.12
2.14
2.16
2.18
2.2
2.22
2.24
Calibrated Airspeed, V_c (knots)
800
820
840
860
880
900
920
940
960
True Airspeed, V_t (knots)
1250
1270
1290
1310
1330
1350

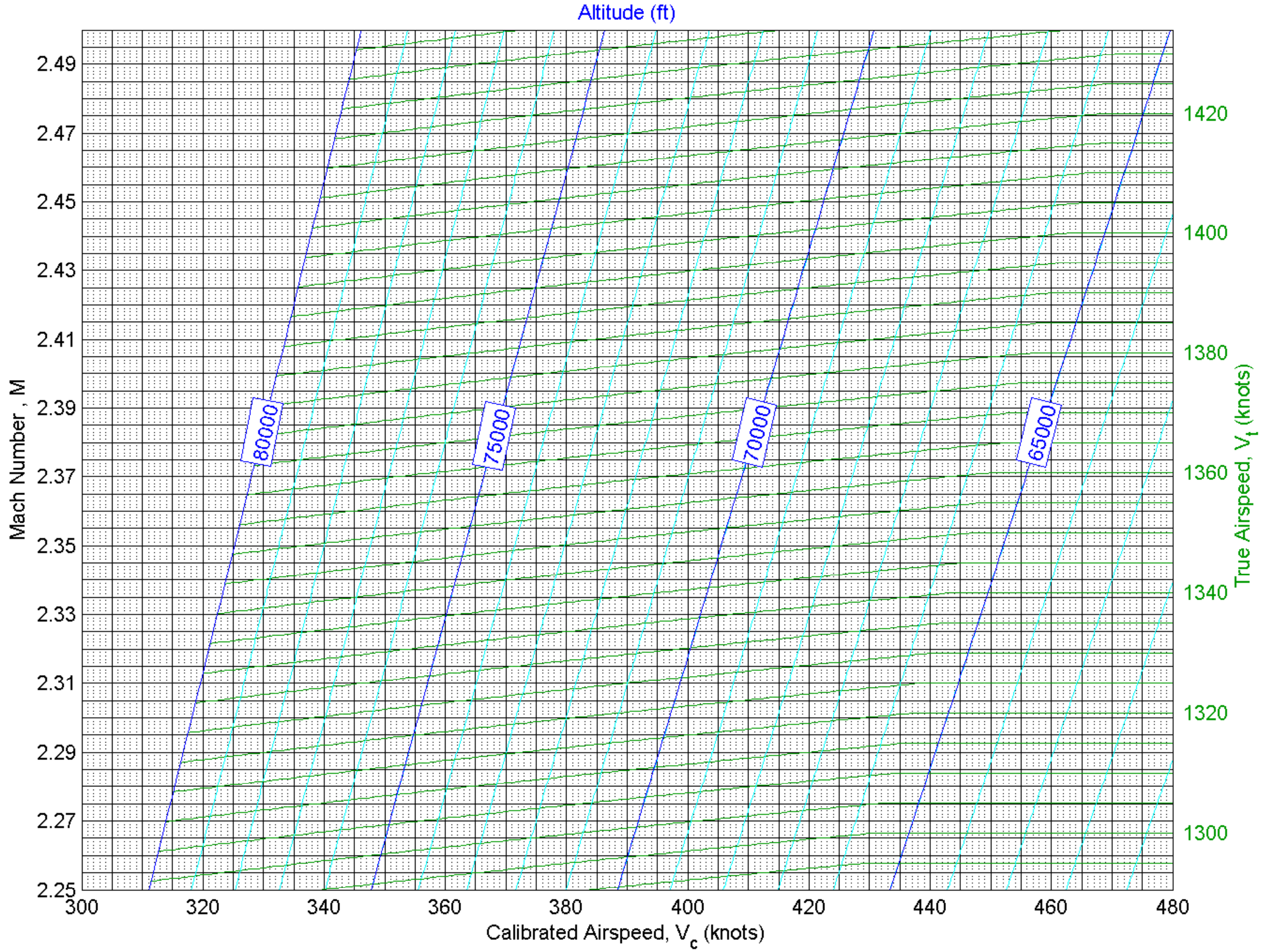

Altitude (ft)
20000
15000
10000
Mach Number, M
2.24
2.22
2.2
2.18
2.16
2.14
2.12
2.1
2.08
2.06
2.04
2.02
2
980
1000
1020
1040
1060
1080
1100
1120
1140
Calibrated Airspeed, V_c (knots)
1400
1380
1360
1340
1320
1300
True Airspeed, V_t (knots)

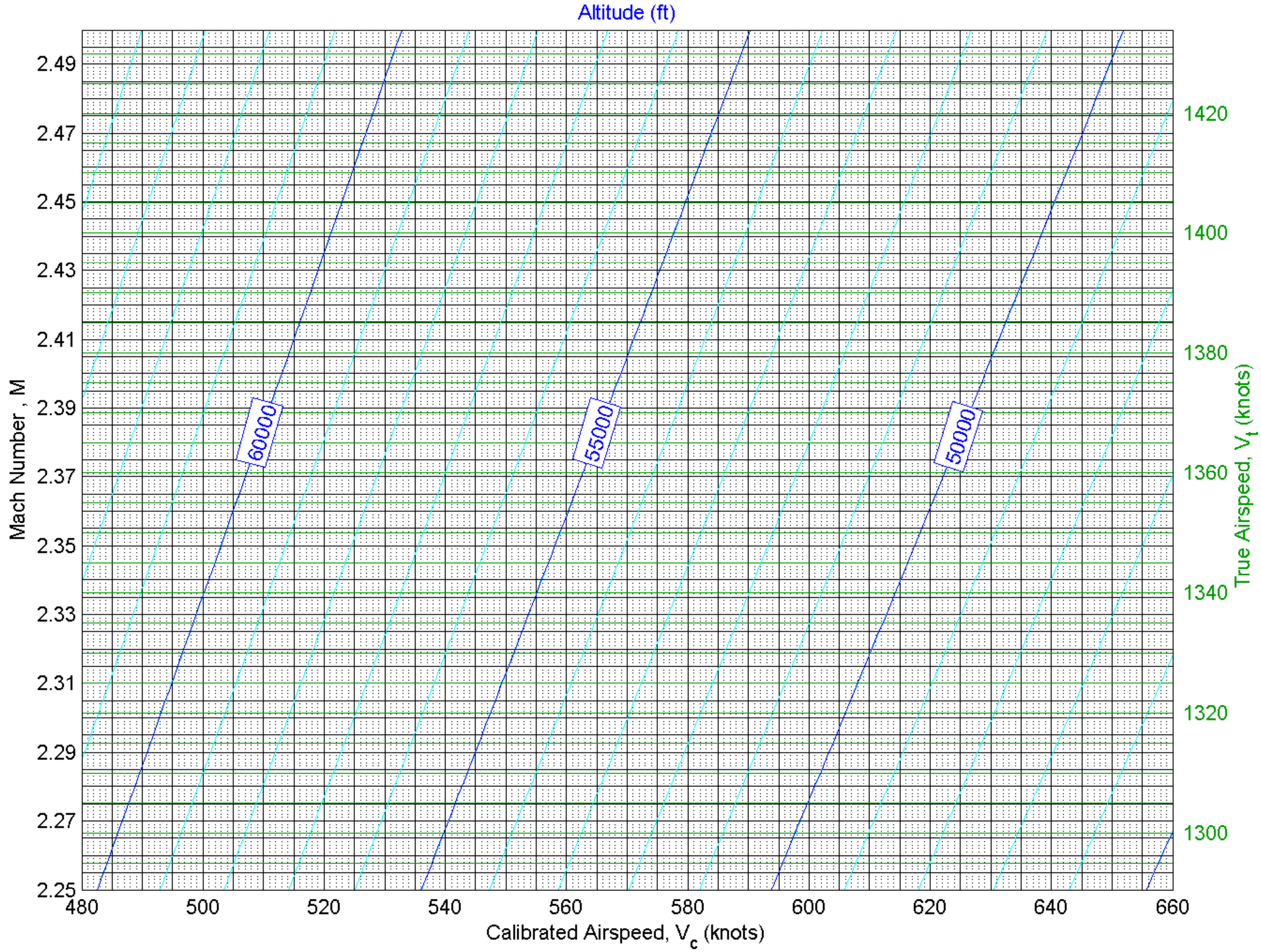


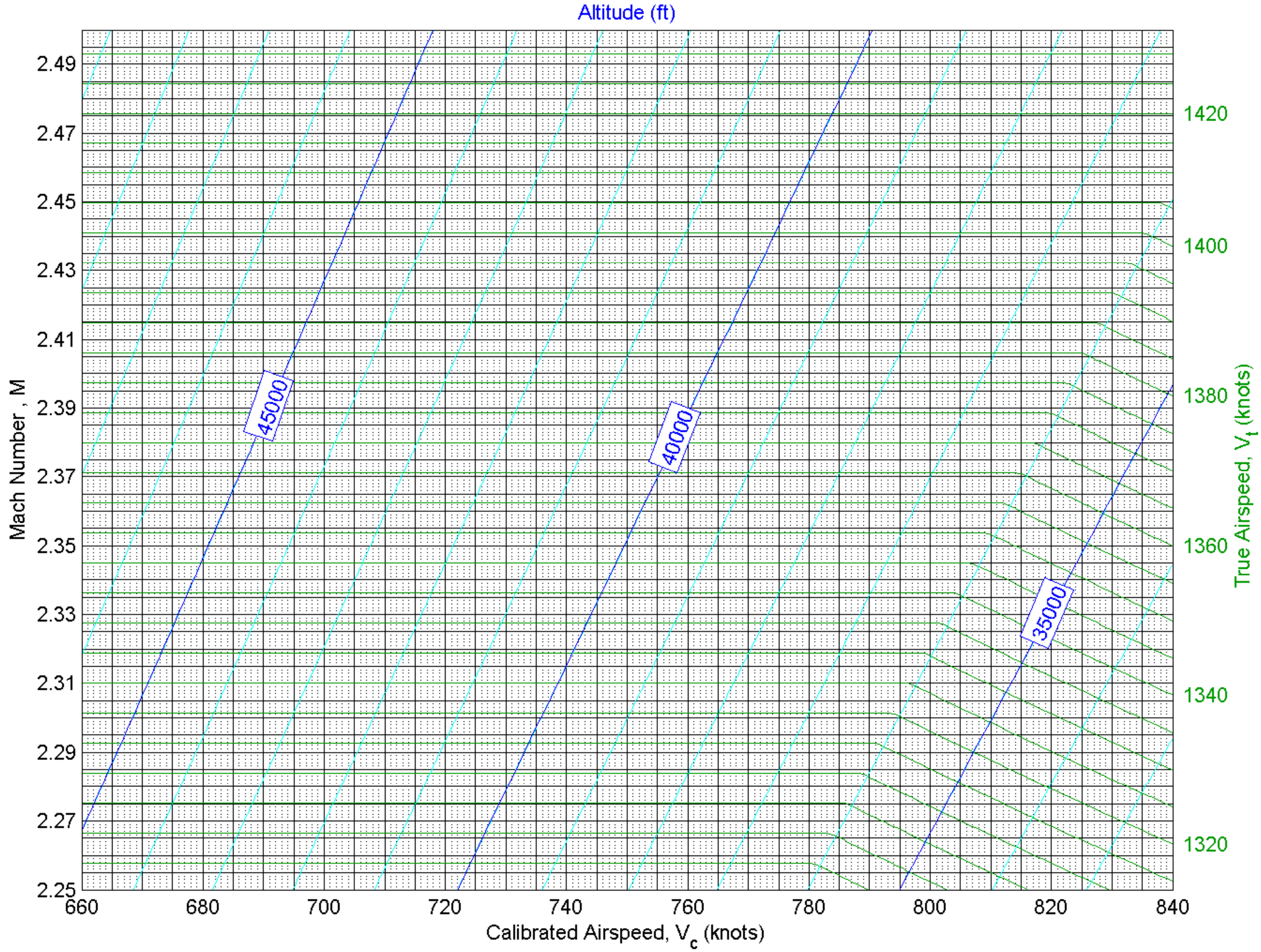
Altitude (ft)
Mach Number, M
2.24
2.22
2.2
2.18
2.16
2.14
2.12
2.1
2.08
2.06
2.04
2.02
2
10000
5000
0
1160
1180
1200
1220
1240
1260
1280
1300
1320
Calibrated Airspeed, V_c (knots)
1440
1420
1400
1380
1360
1340
True Airspeed, V_t (knots)

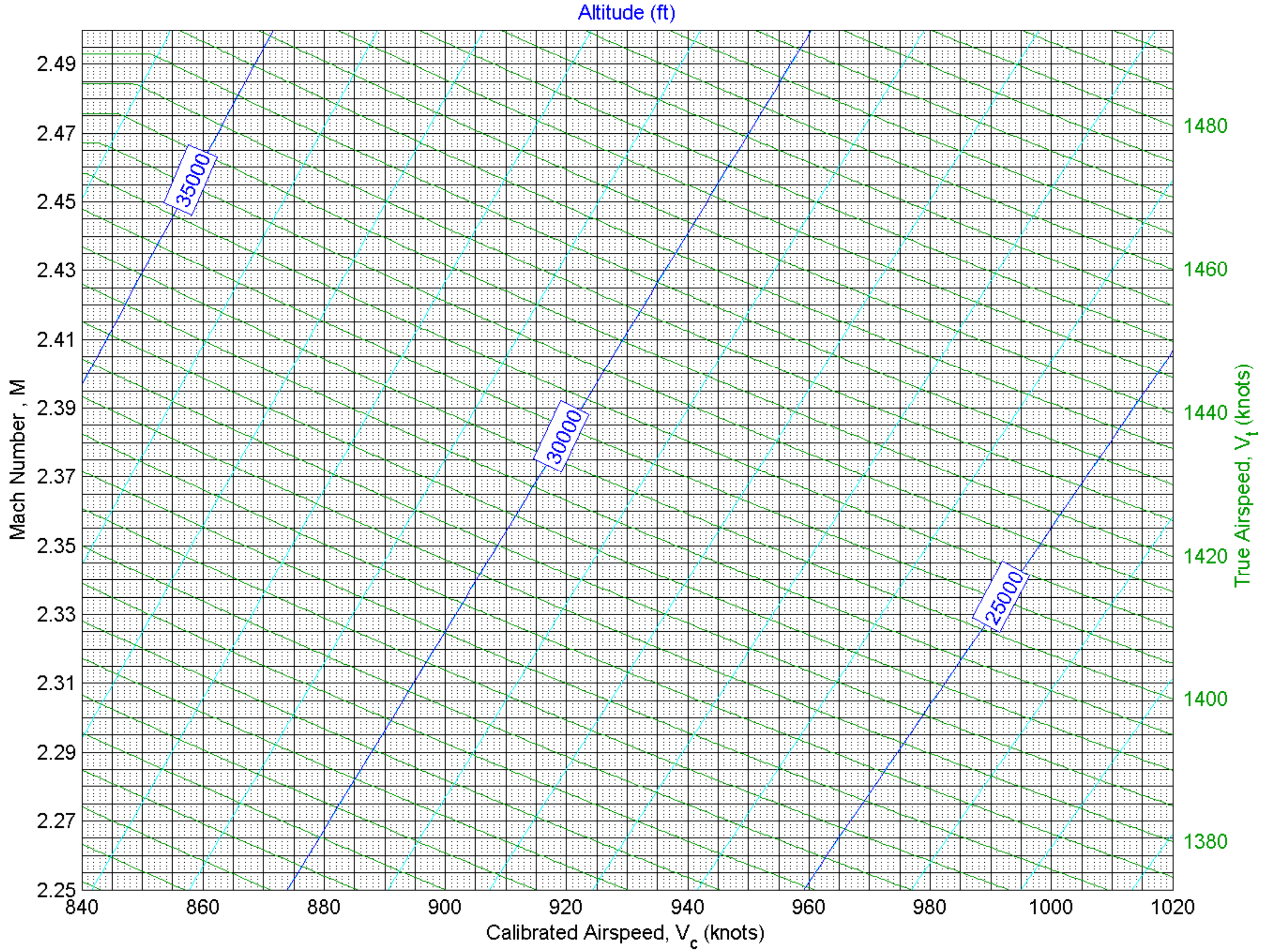


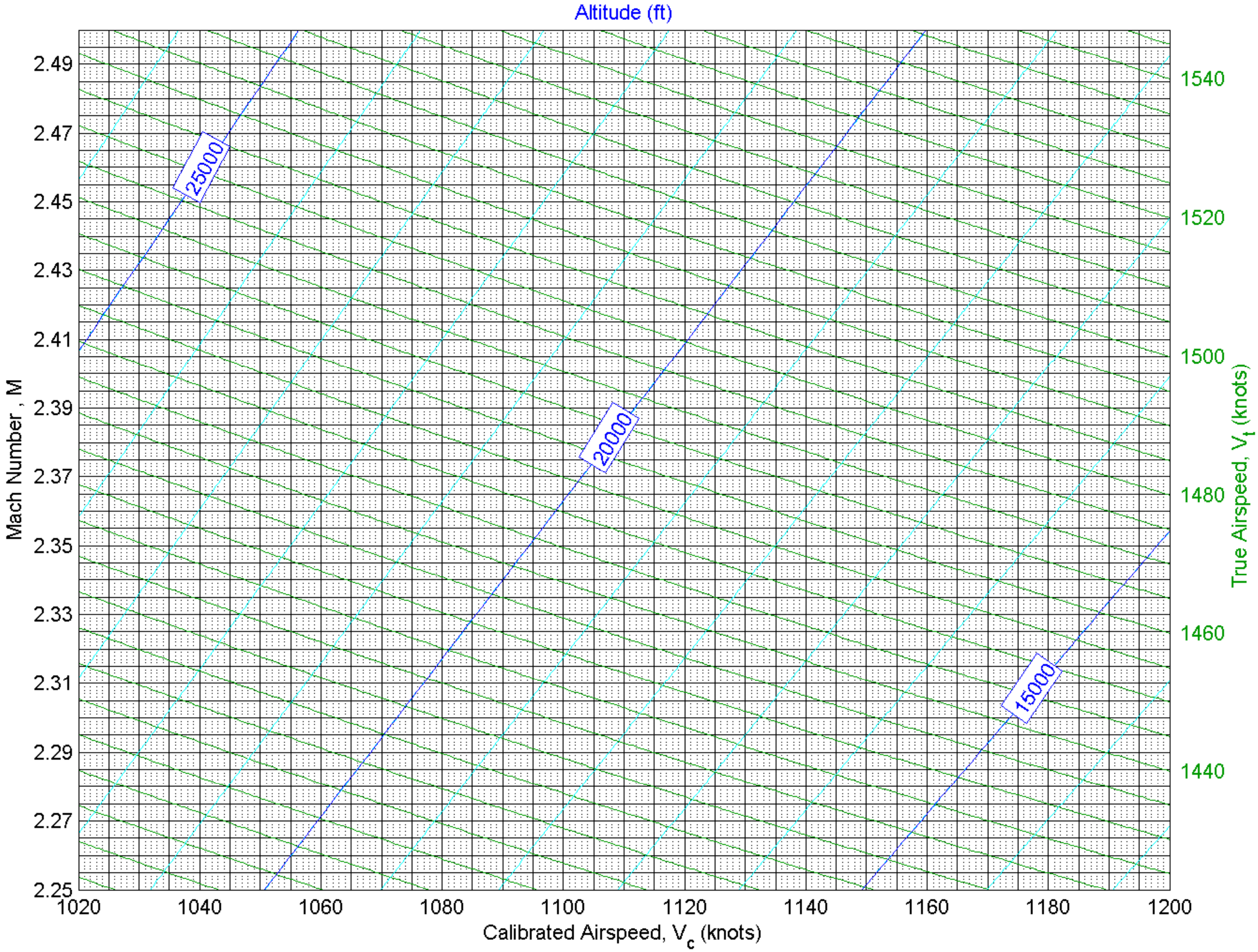
Altitude (ft)
5000
0
1340
1360
1380
1400
1420
1440
1460
1480
True Airspeed, V_t (knots)
Mach Number , M
2
2.02
2.04
2.06
2.08
2.1
2.12
2.14
2.16
2.18
2.2
2.22
2.24
1340
1360
1380
1400
1420
1440
1460
1480
1500
Calibrated Airspeed, V_c (knots)

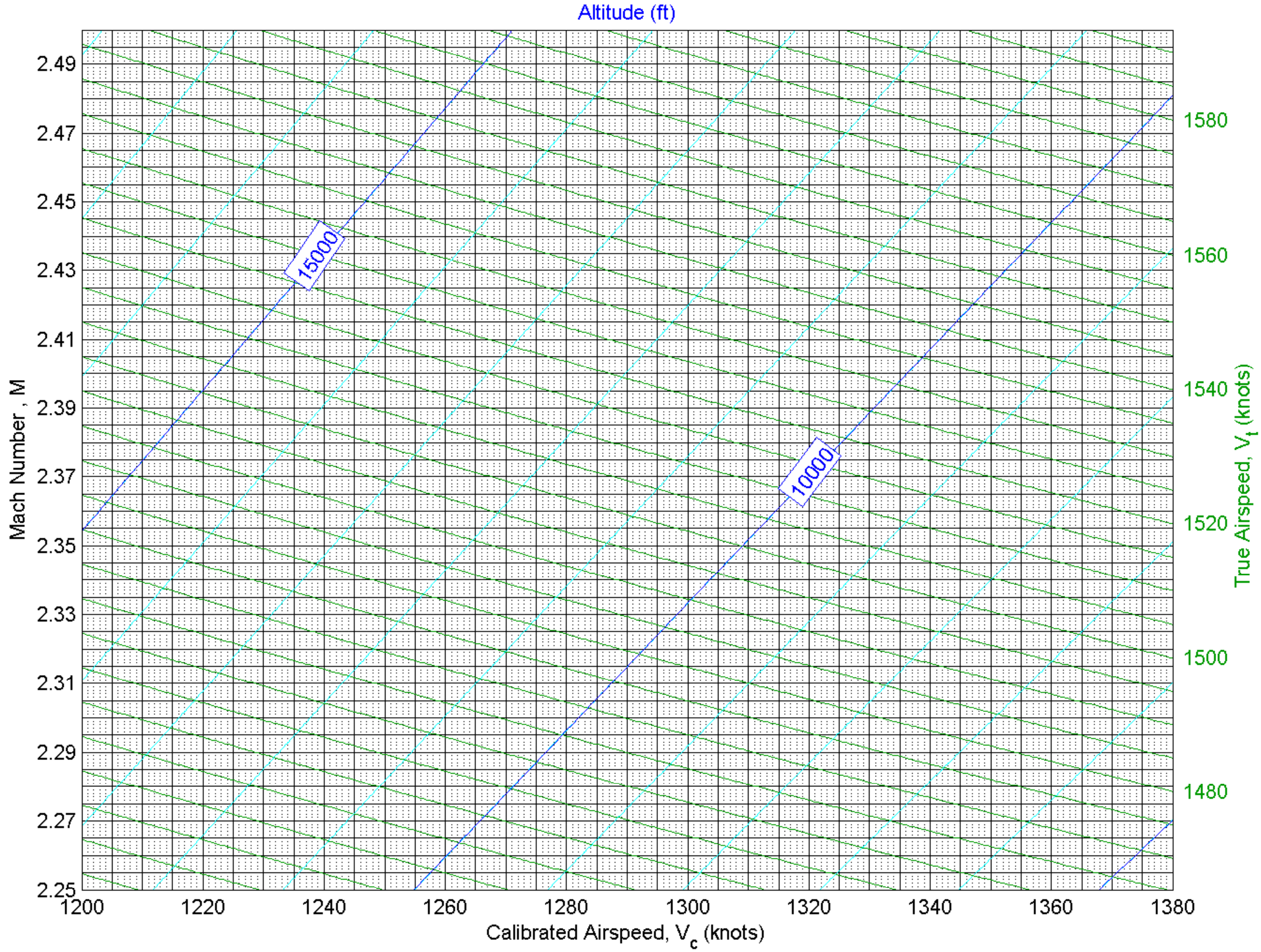

Altitude (ft)
80000
75000
70000
65000
Mach Number , M
2.49
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
300
320
340
360
380
400
420
440
460
480
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1420
1400
1380
1360
1340
1320
1300

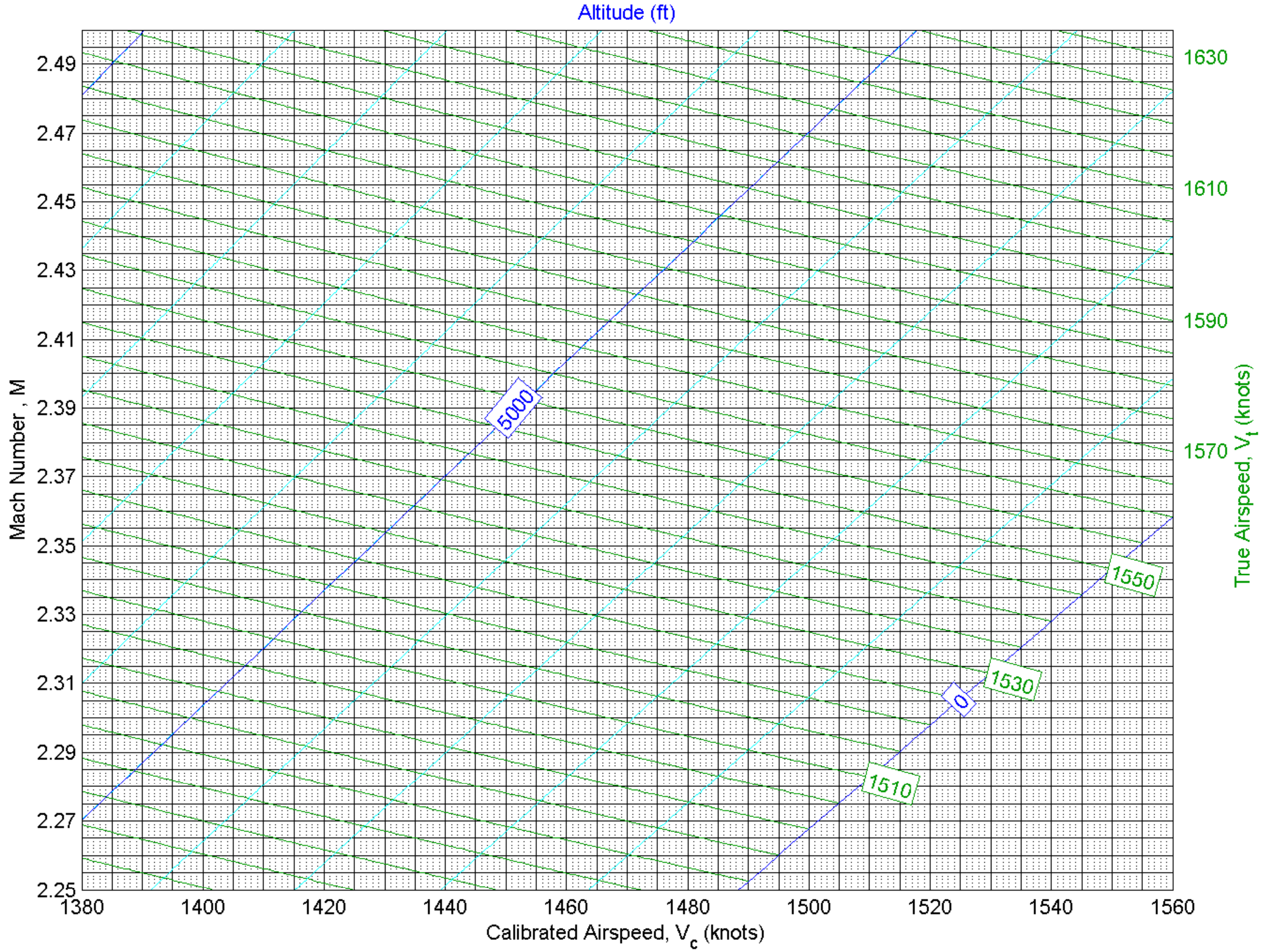

Altitude (ft)
60000
55000
50000
Mach Number , M
2.49
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
True Airspeed, V_t (knots)
1420
1400
1380
1360
1340
1320
1300
480
500
520
540
560
580
600
620
640
660
Calibrated Airspeed, V_c (knots)


Altitude (ft)
Mach Number , M
2.49
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
660
680
700
720
740
760
780
800
820
840
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1420
1400
1380
1360
1340
1320
45000
40000
35000


Altitude (ft)
35000
30000
25000
2.49
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
Mach Number , M
1480
1460
1440
1420
1400
1380
True Airspeed, V_t (knots)
840
860
880
900
920
940
960
980
1000
1020
Calibrated Airspeed, V_c (knots)


Altitude (ft)
25000
20000
15000
Mach Number , M
2.25
2.27
2.29
2.31
2.33
2.35
2.37
2.39
2.41
2.43
2.45
2.47
2.49
True Airspeed, V_t (knots)
1440
1460
1480
1500
1520
1540
Calibrated Airspeed, V_c (knots)
1020
1040
1060
1080
1100
1120
1140
1160
1180
1200


Altitude (ft)
15000
10000
Mach Number , M
2.49
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1580
1560
1540
1520
1500
1480


Altitude (ft)
Mach Number , M
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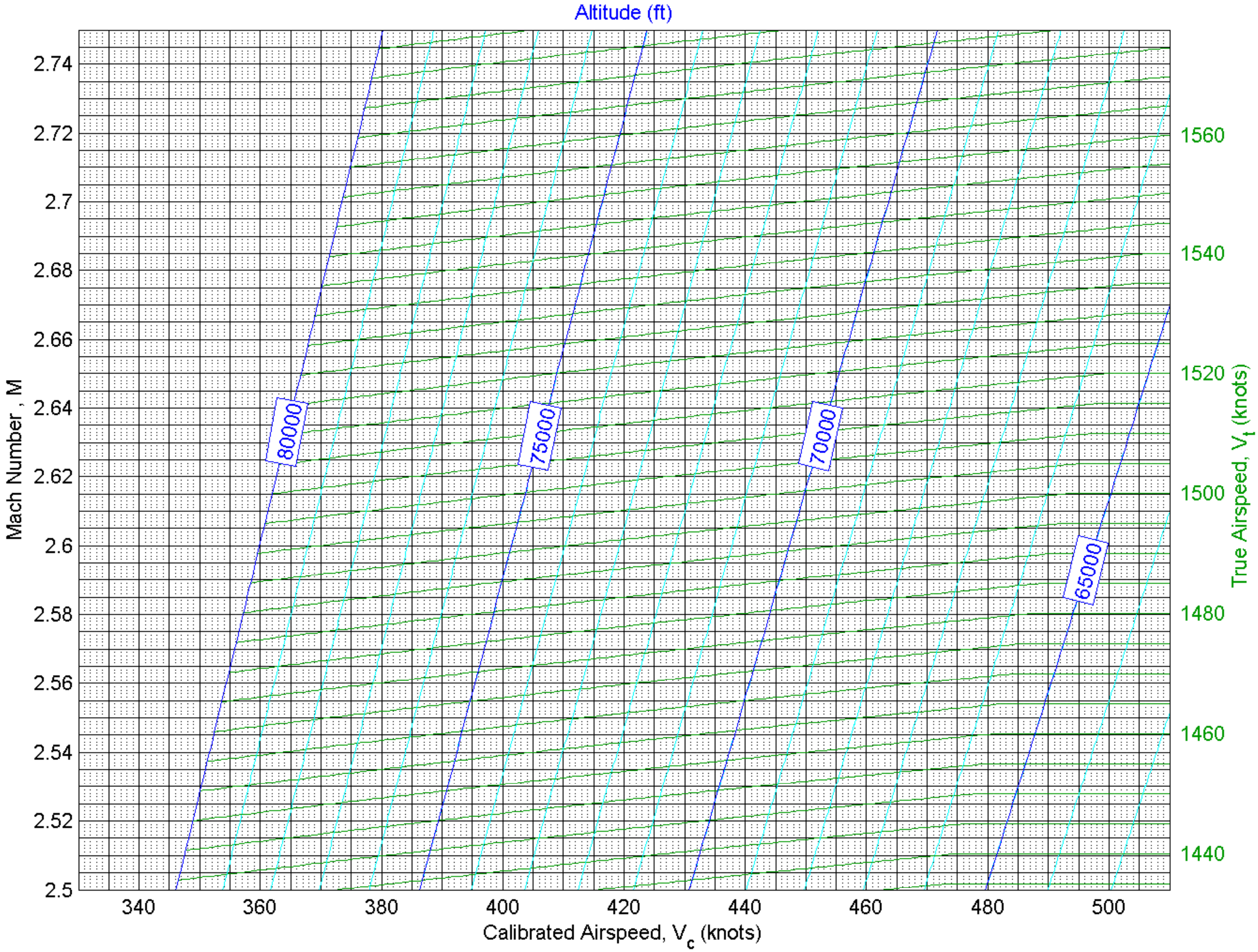
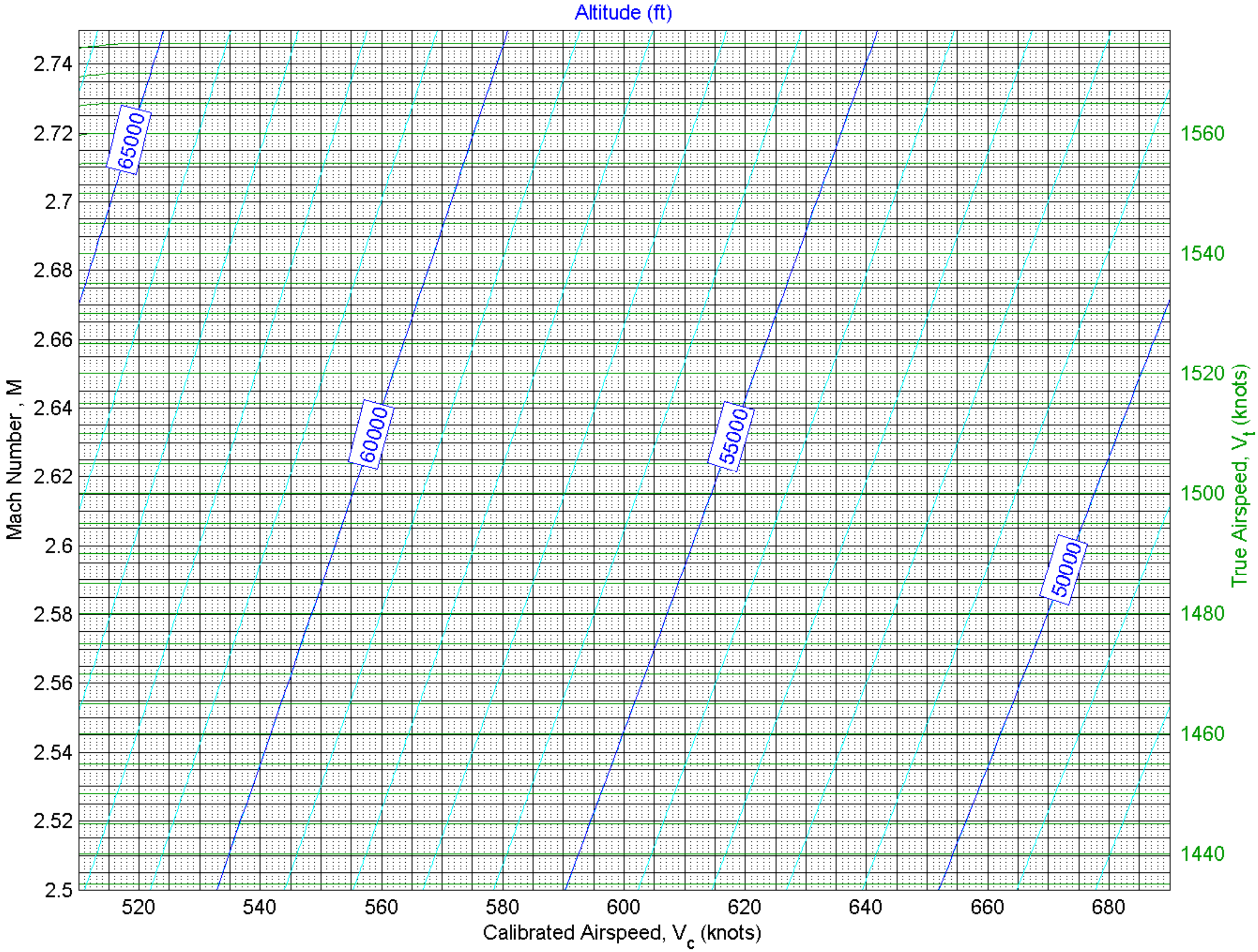
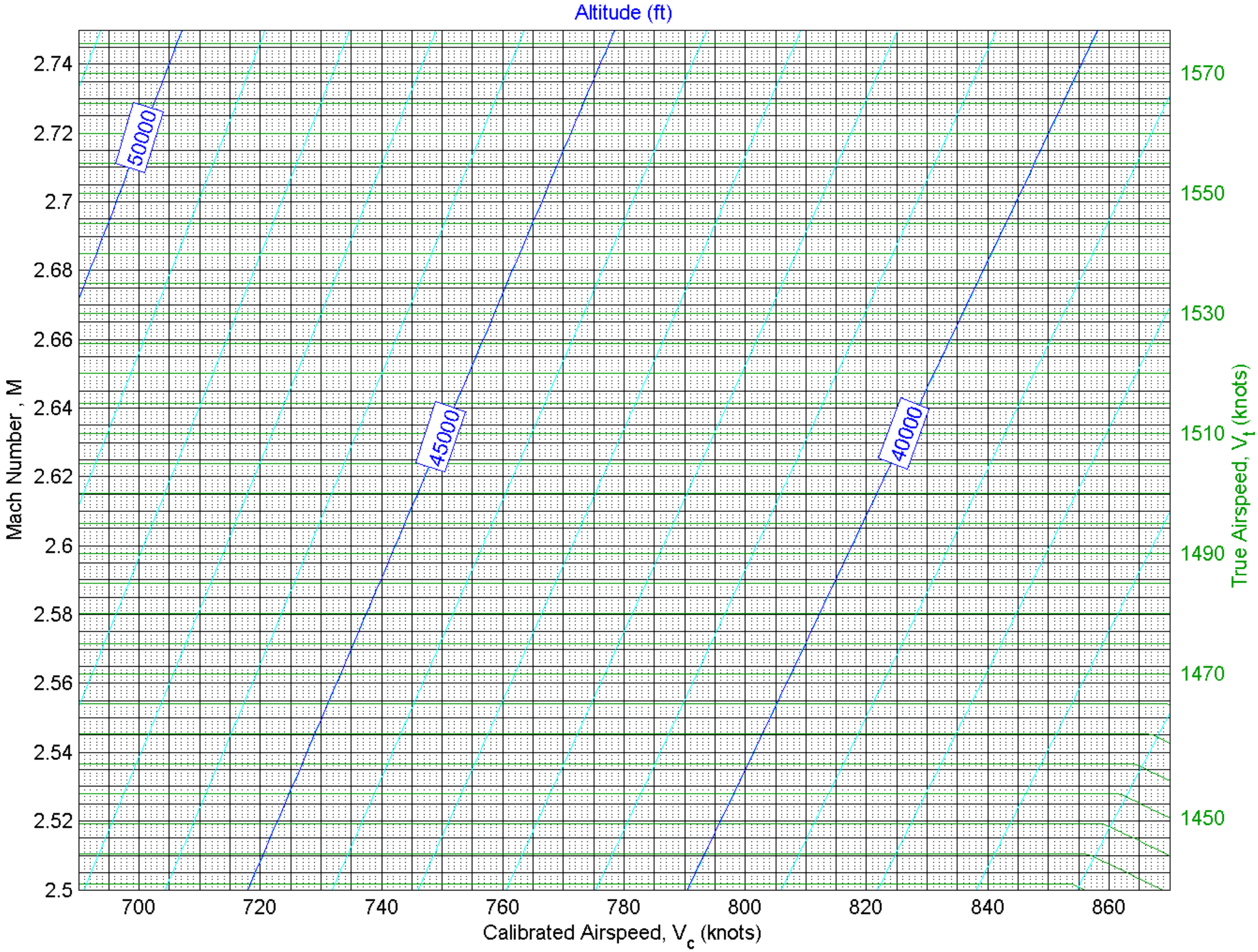
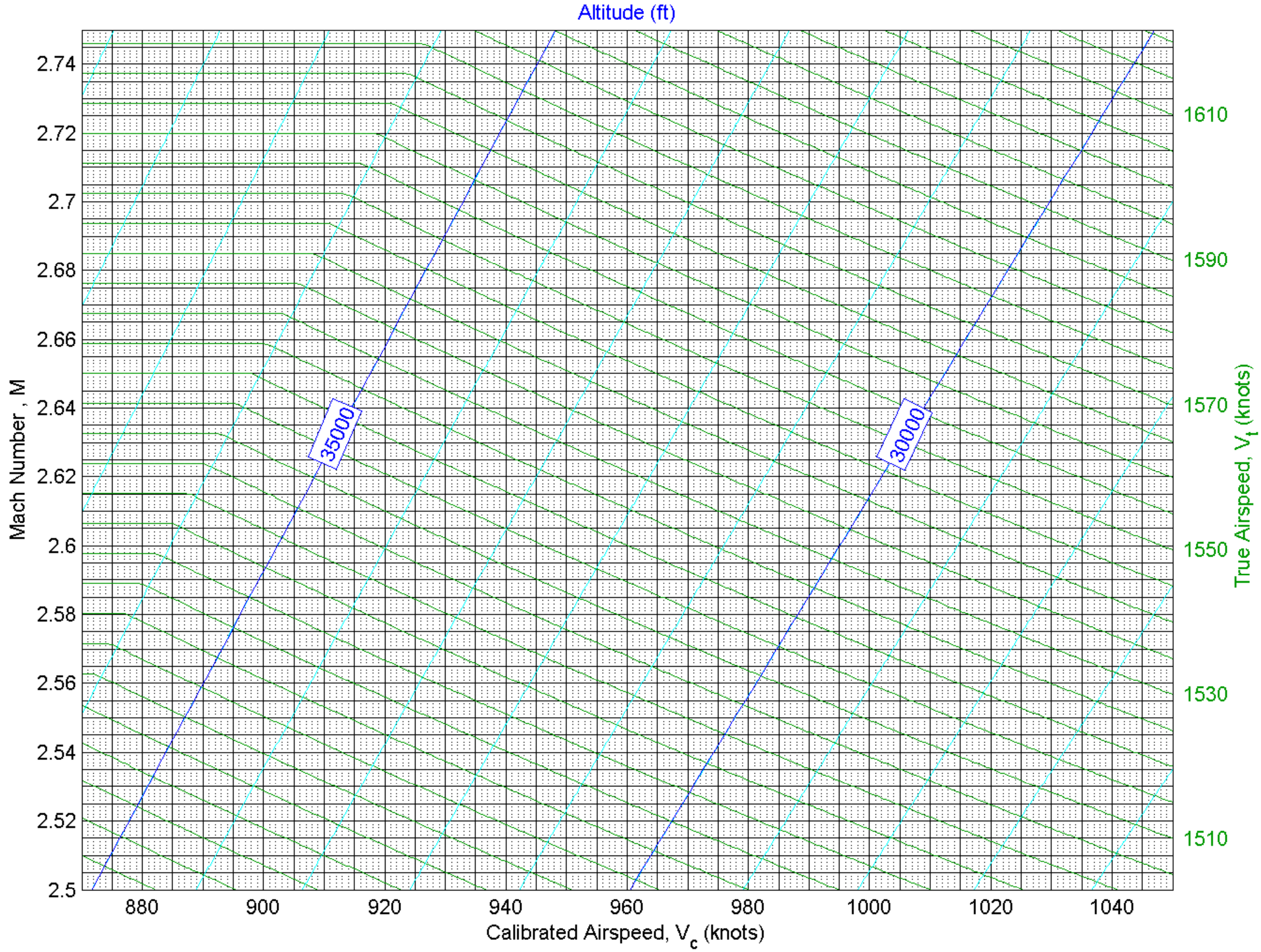
2.47
2.45
2.43
2.41
2.39
2.37
2.35
2.33
2.31
2.29
2.27
2.25
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1630
1610
1590
1570
1550
1530
1510
5000
0


Altitude (ft)
80000
75000
70000
65000
Mach Number , M
2.5
2.52
2.54
2.56
2.58
2.6
2.62
2.64
2.66
2.68
2.7
2.72
2.74
340
360
380
400
420
440
460
480
500
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1440
1460
1480
1500
1520
1540
1560

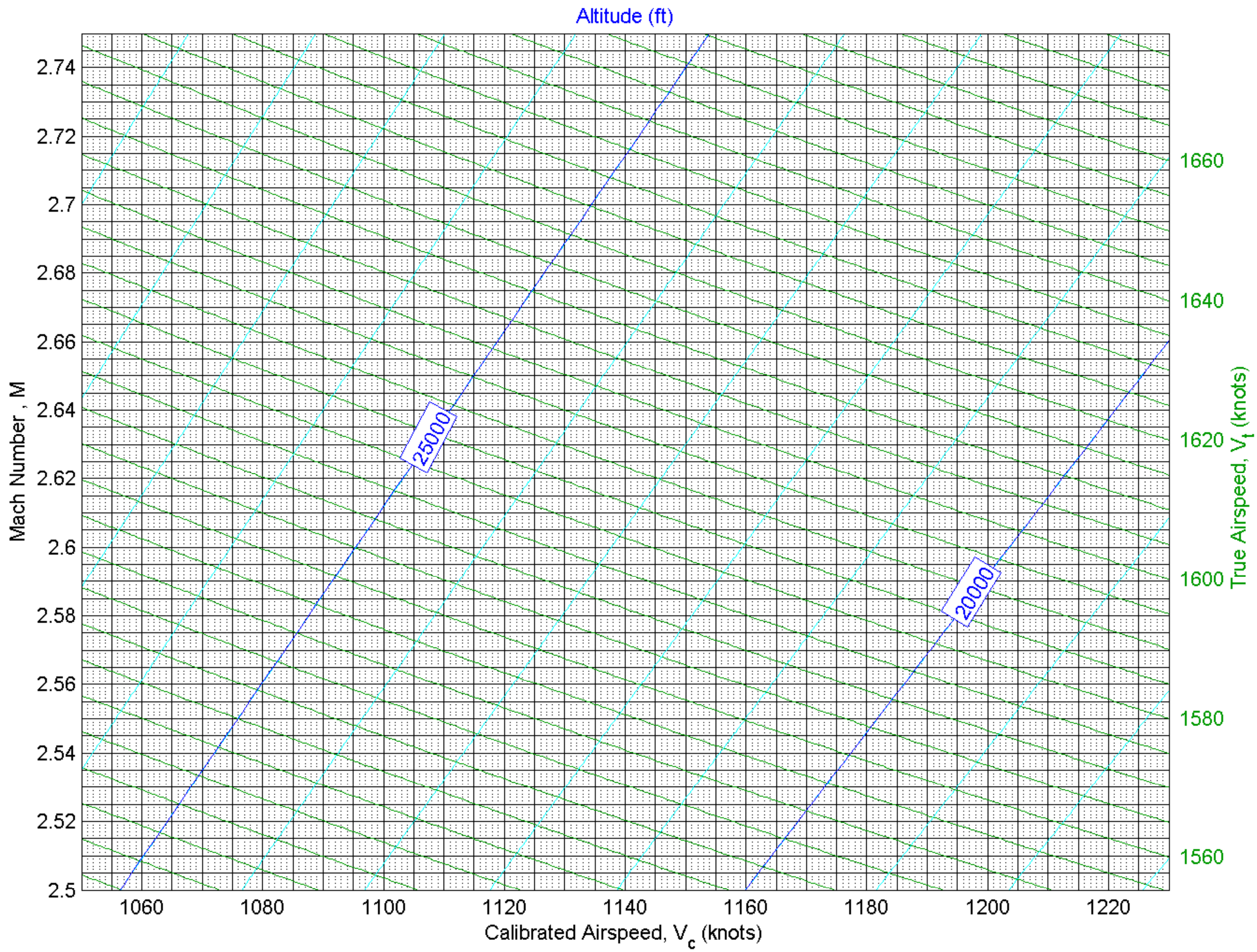

Altitude (ft)
65000
60000
55000
50000
Mach Number , M
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
True Airspeed, V_t (knots)
1560
1540
1520
1500
1480
1460
1440
520
540
560
580
600
620
640
660
680
Calibrated Airspeed, V_c (knots)



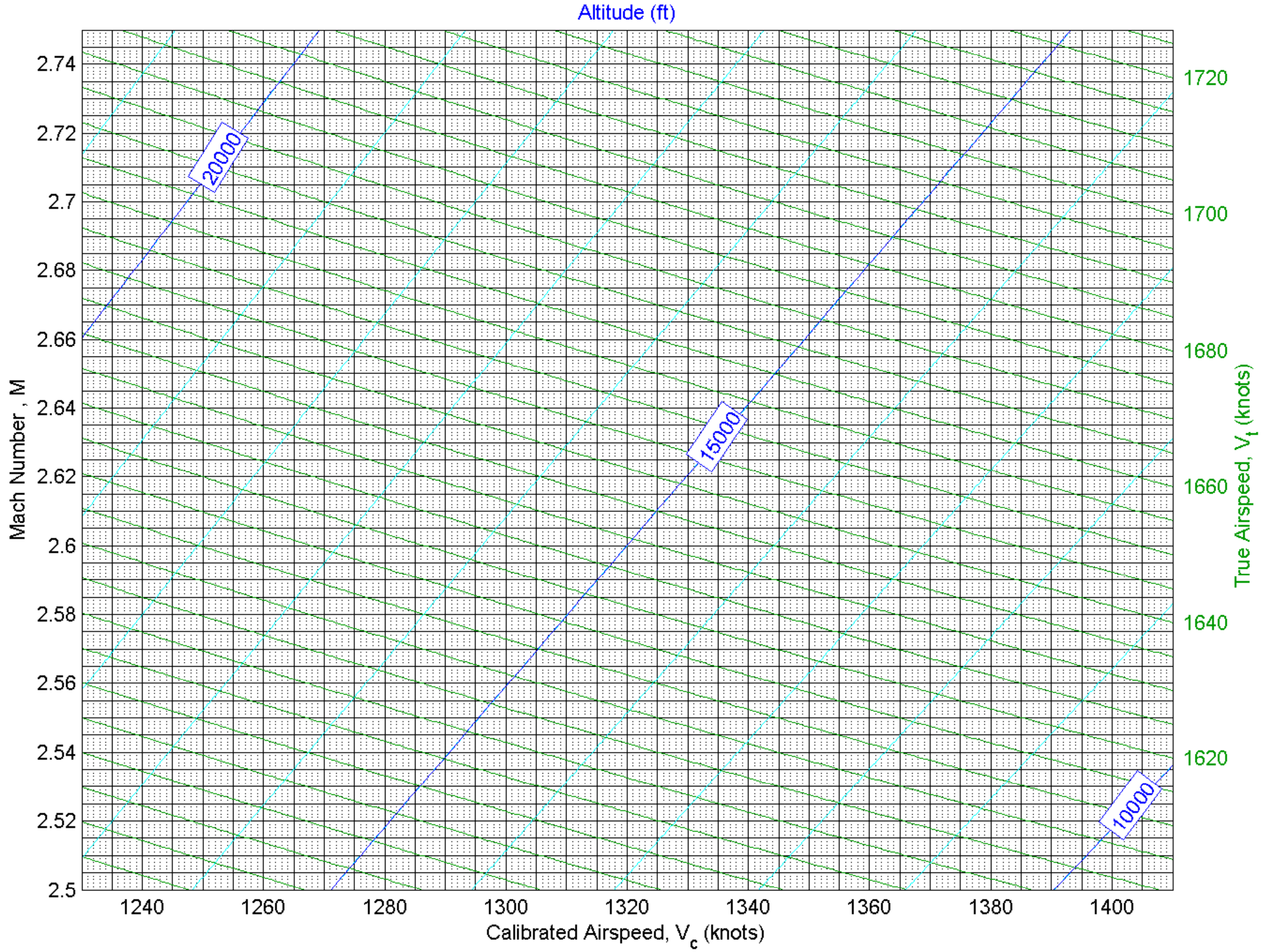
Altitude (ft)
50000
45000
40000
Mach Number , M
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
700
720
740
760
780
800
820
840
860
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1570
1550
1530
1510
1490
1470
1450



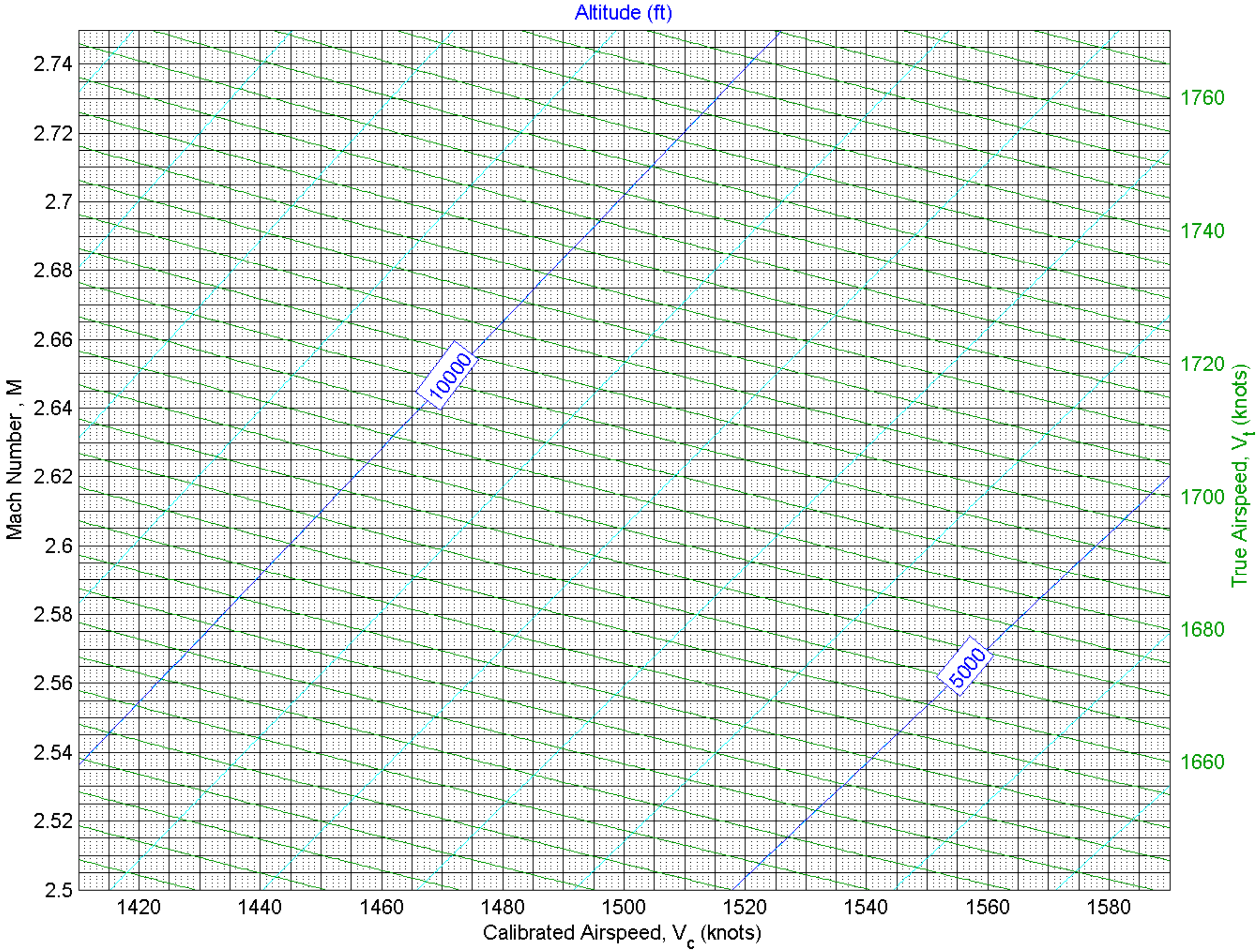
Altitude (ft)
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
Mach Number , M
35000
30000
1610
1590
1570
1550
1530
1510
True Airspeed, V_t (knots)
880
900
920
940
960
980
1000
1020
1040
Calibrated Airspeed, V_c (knots)

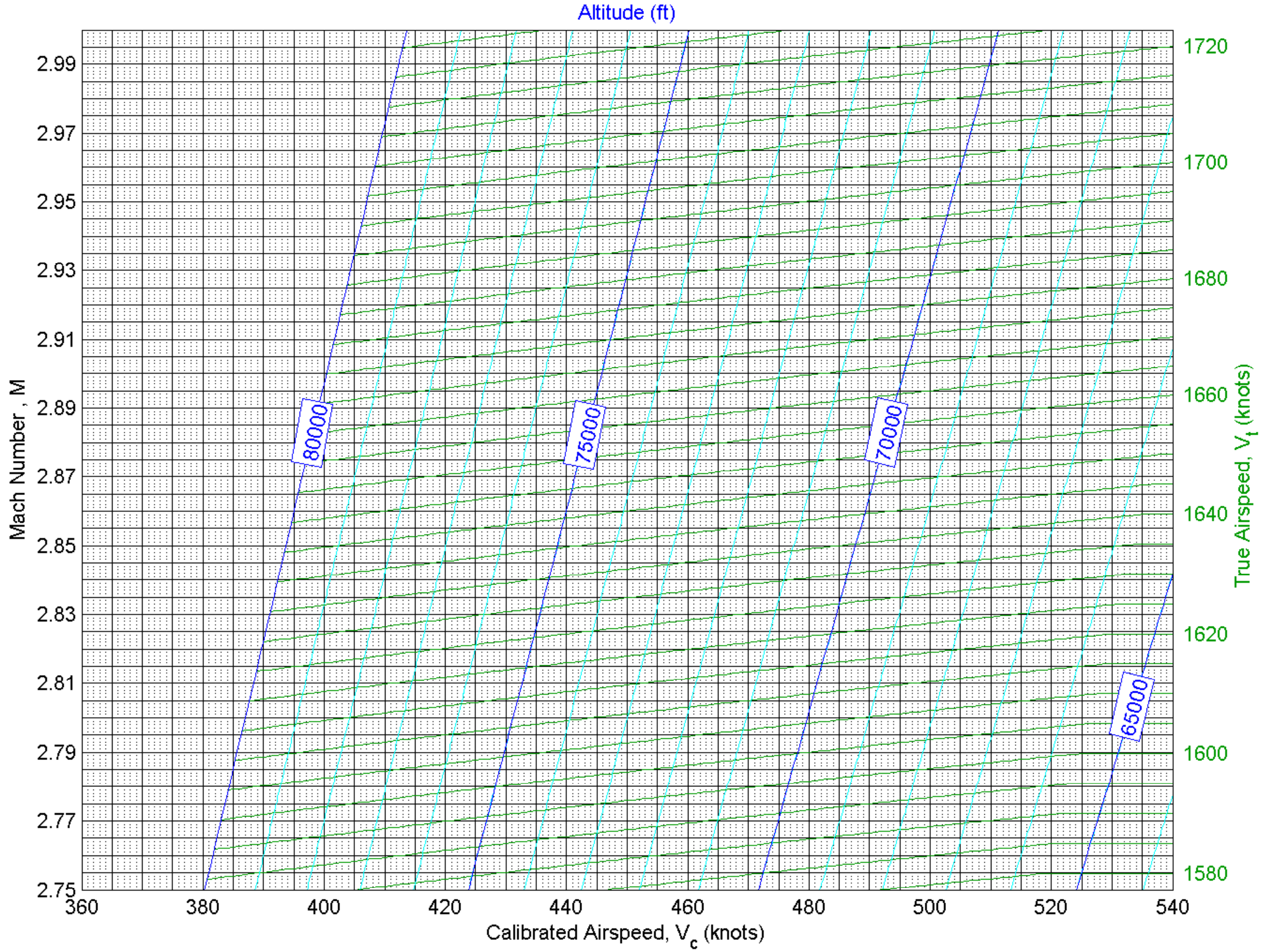


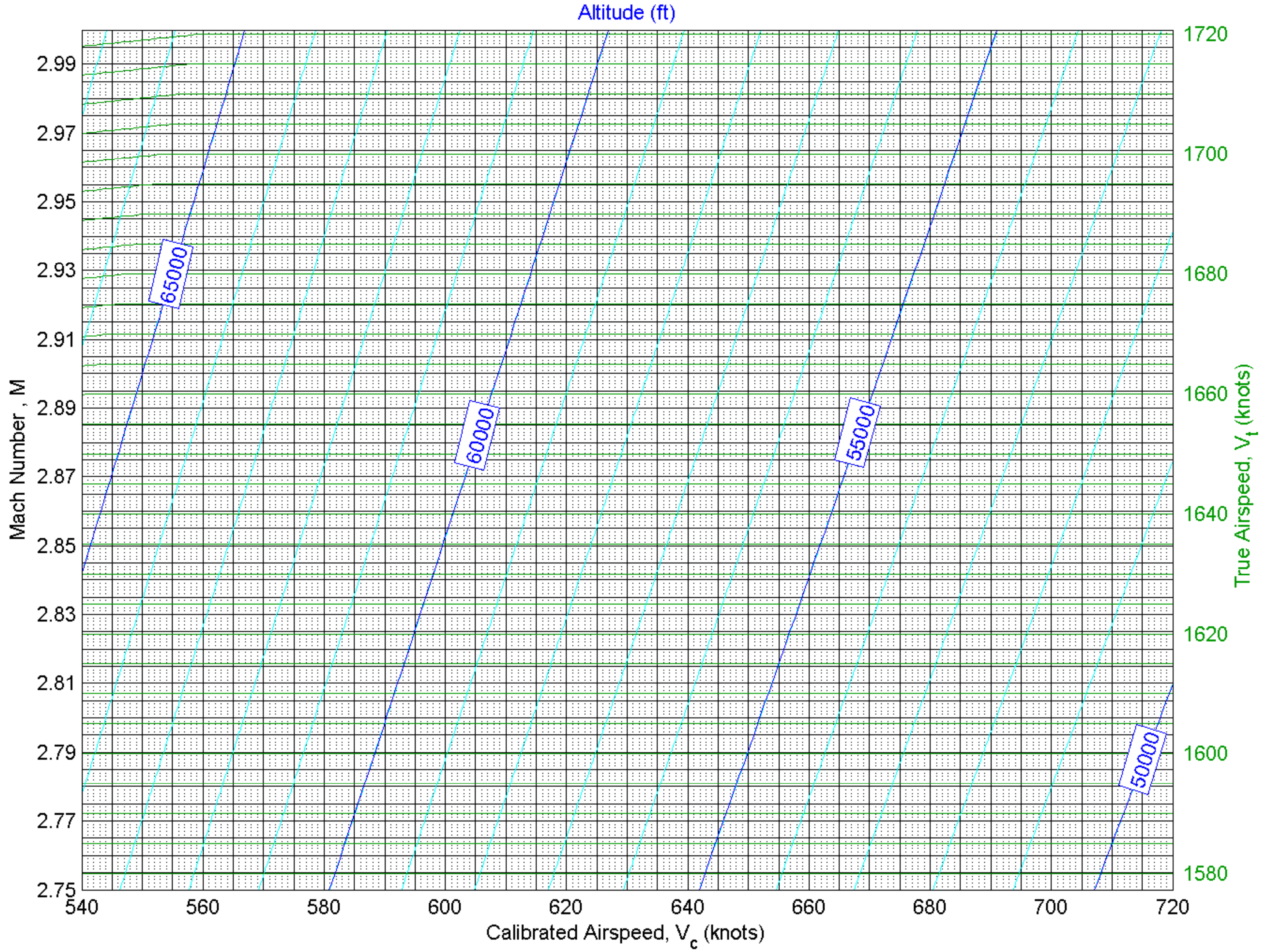
Altitude (ft)
Mach Number, M
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
1060
1080
1100
1120
1140
1160
1180
1200
1220
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1660
1640
1620
1600
1580
1560
25000
20000



Altitude (ft)
20000
15000
10000
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
Mach Number , M
1240
1260
1280
1300
1320
1340
1360
1380
1400
Calibrated Airspeed, V_c (knots)
1720
1700
1680
1660
1640
1620
True Airspeed, V_t (knots)


Altitude (ft)
10000
5000
Mach Number , M
2.74
2.72
2.7
2.68
2.66
2.64
2.62
2.6
2.58
2.56
2.54
2.52
2.5
1420
1440
1460
1480
1500
1520
1540
1560
1580
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1760
1740
1720
1700
1680
1660


Altitude (ft)
80000
75000
70000
65000
Mach Number , M
2.99
2.97
2.95
2.93
2.91
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
Calibrated Airspeed, V_c (knots)
360
380
400
420
440
460
480
500
520
540
True Airspeed, V_t (knots)
1720
1700
1680
1660
1640
1620
1600
1580



Altitude (ft)
Mach Number, M
True Airspeed, V_t (knots)
Calibrated Airspeed, V_c (knots)
65000
60000
55000
50000
2.75
2.77
2.79
2.81
2.83
2.85
2.87
2.89
2.91
2.93
2.95
2.97
2.99
540
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620
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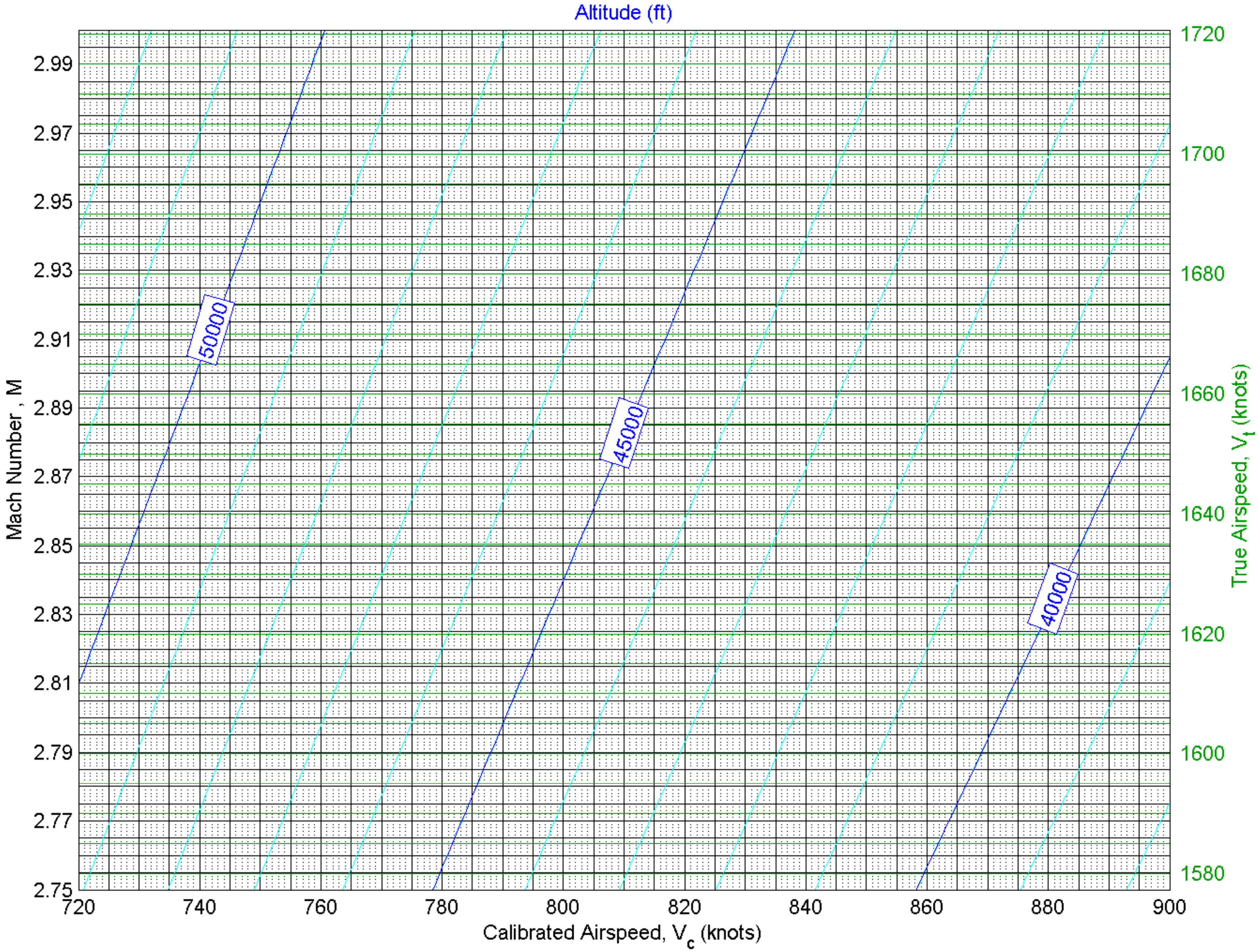
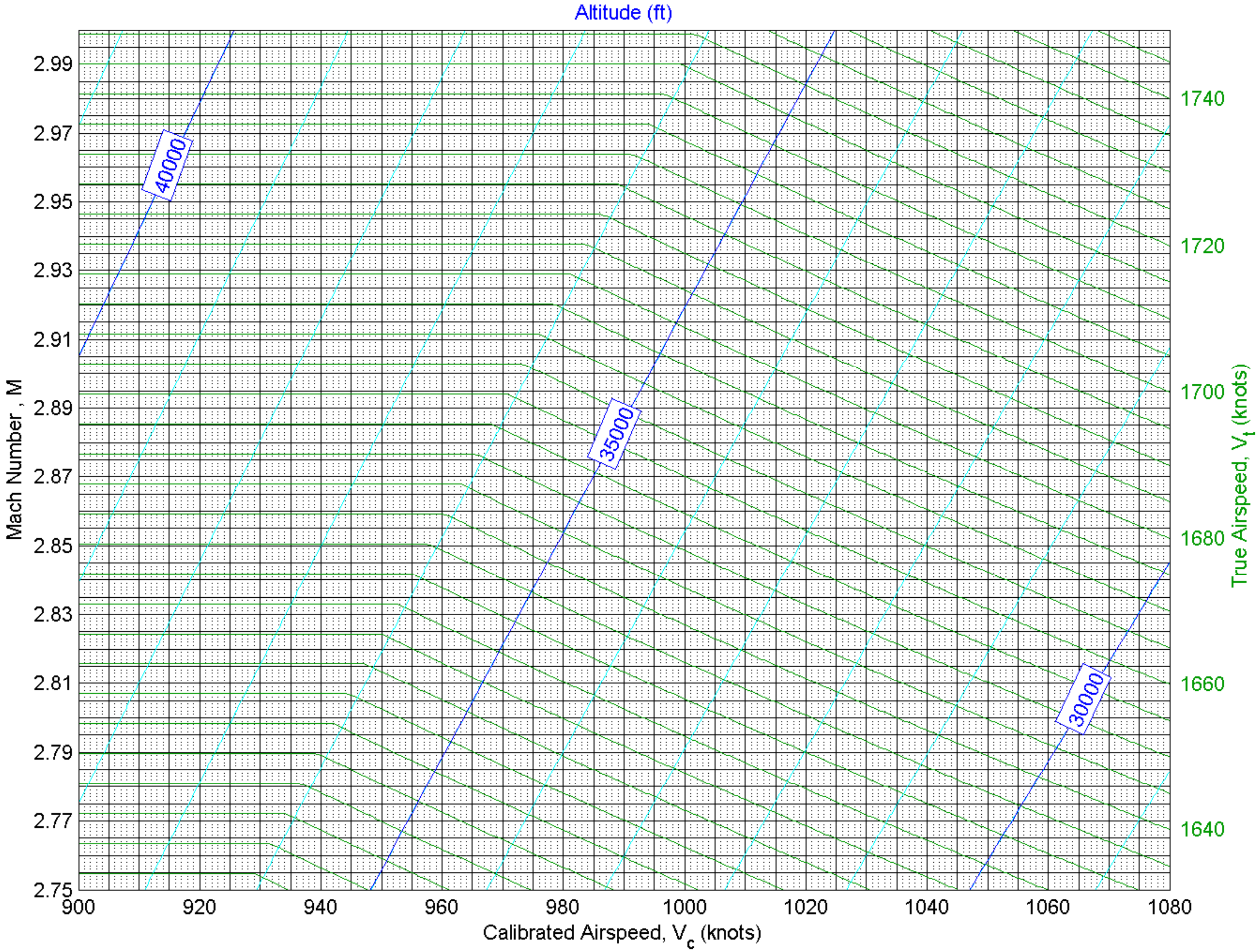
1660
1680
1700
1720



Altitude (ft)
50000
45000
40000
Mach Number , M
2.99
2.97
2.95
2.93
2.91
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
720
740
760
780
800
820
840
860
880
900
Calibrated Airspeed, V_c (knots)
1720
1700
1680
1660
1640
1620
1600
1580
True Airspeed, V_t (knots)


Altitude (ft)
40000
35000
30000
2.99
2.97
2.95
2.93
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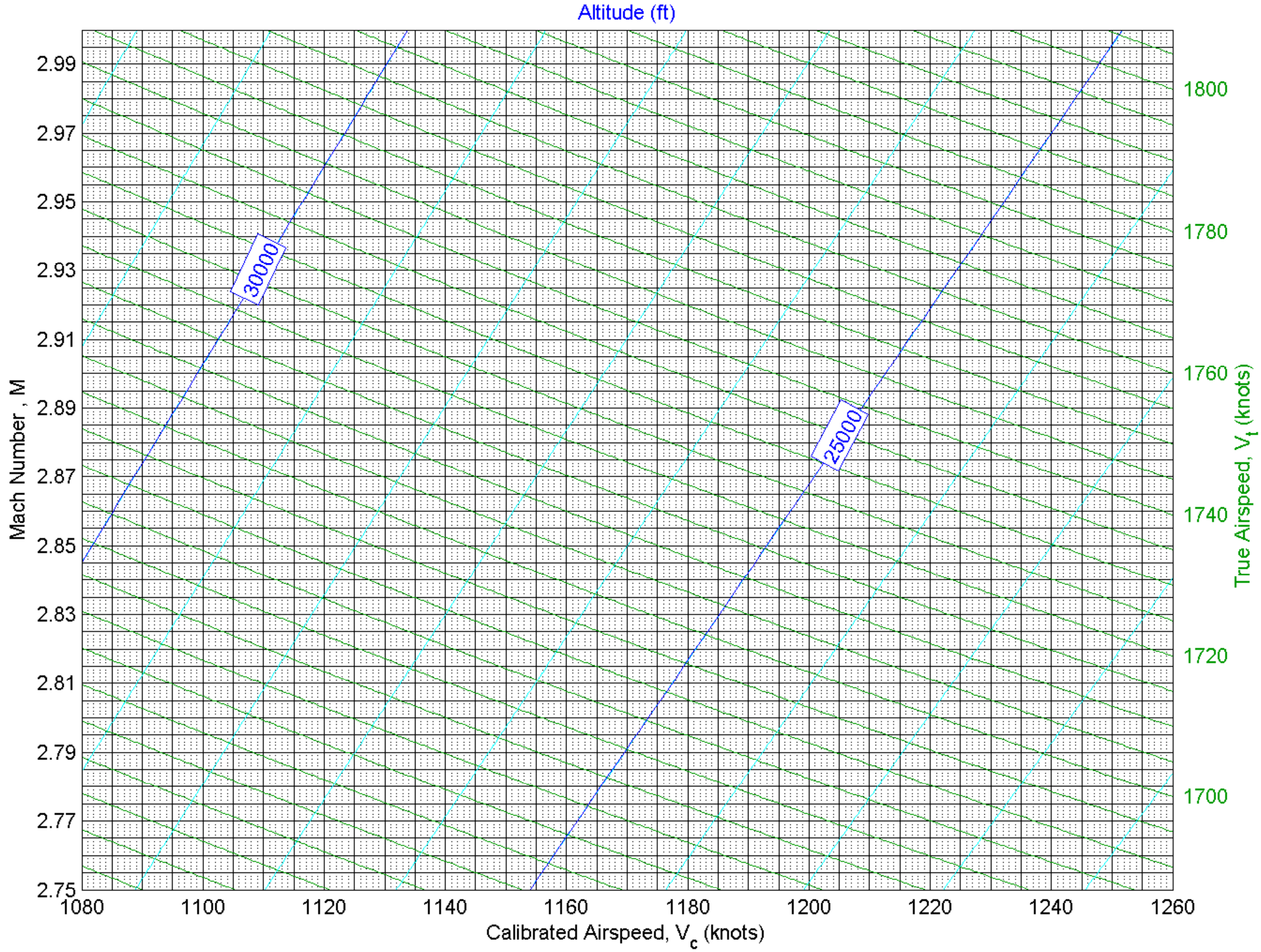
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
Mach Number , M
900
920
940
960
980
1000
1020
1040
1060
1080
Calibrated Airspeed, V_c (knots)
1740
1720
1700
1680
1660
1640
True Airspeed, V_t (knots)


Altitude (ft)
30000
25000
Mach Number , M
2.99
2.97
2.95
2.93
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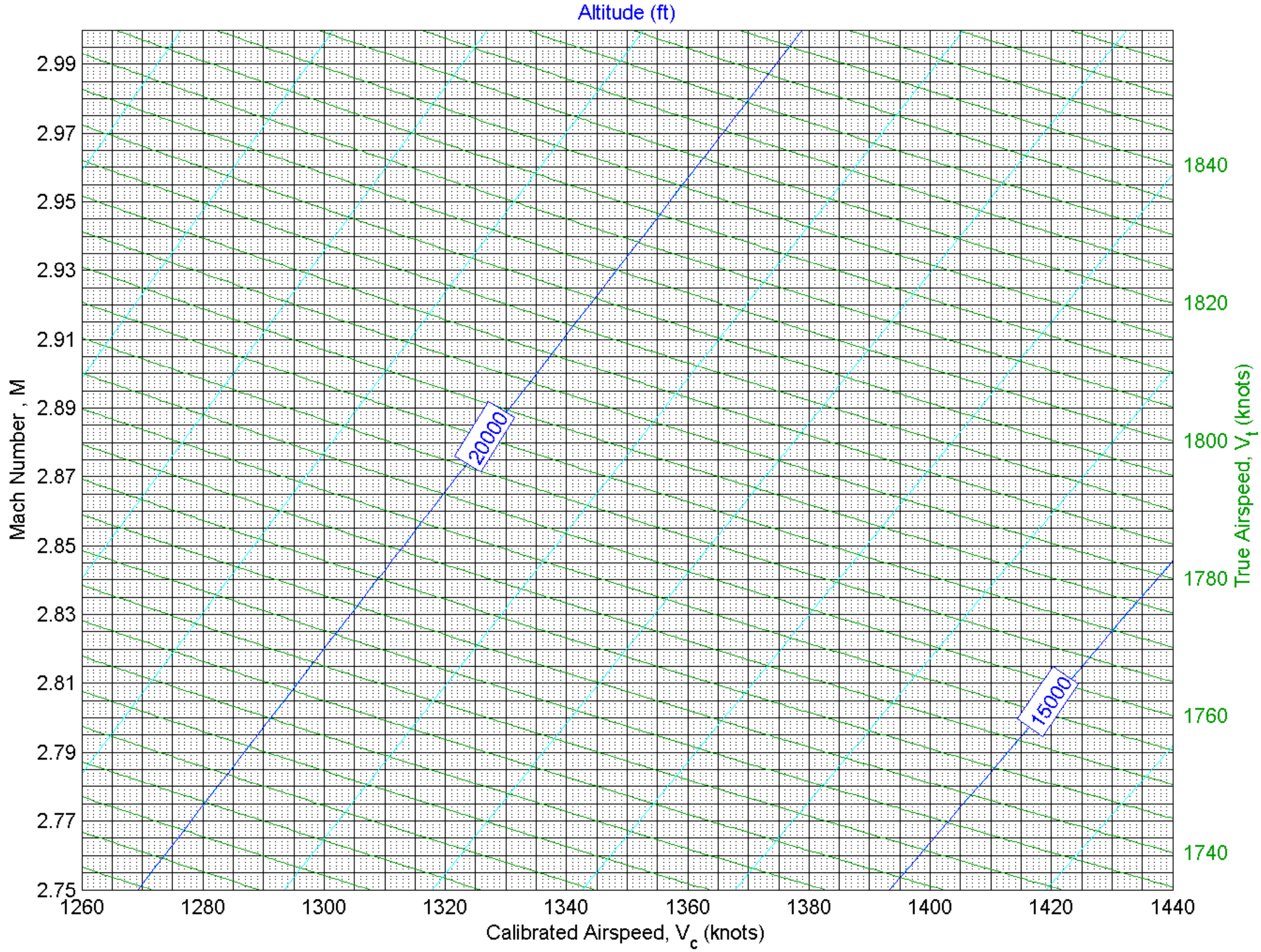
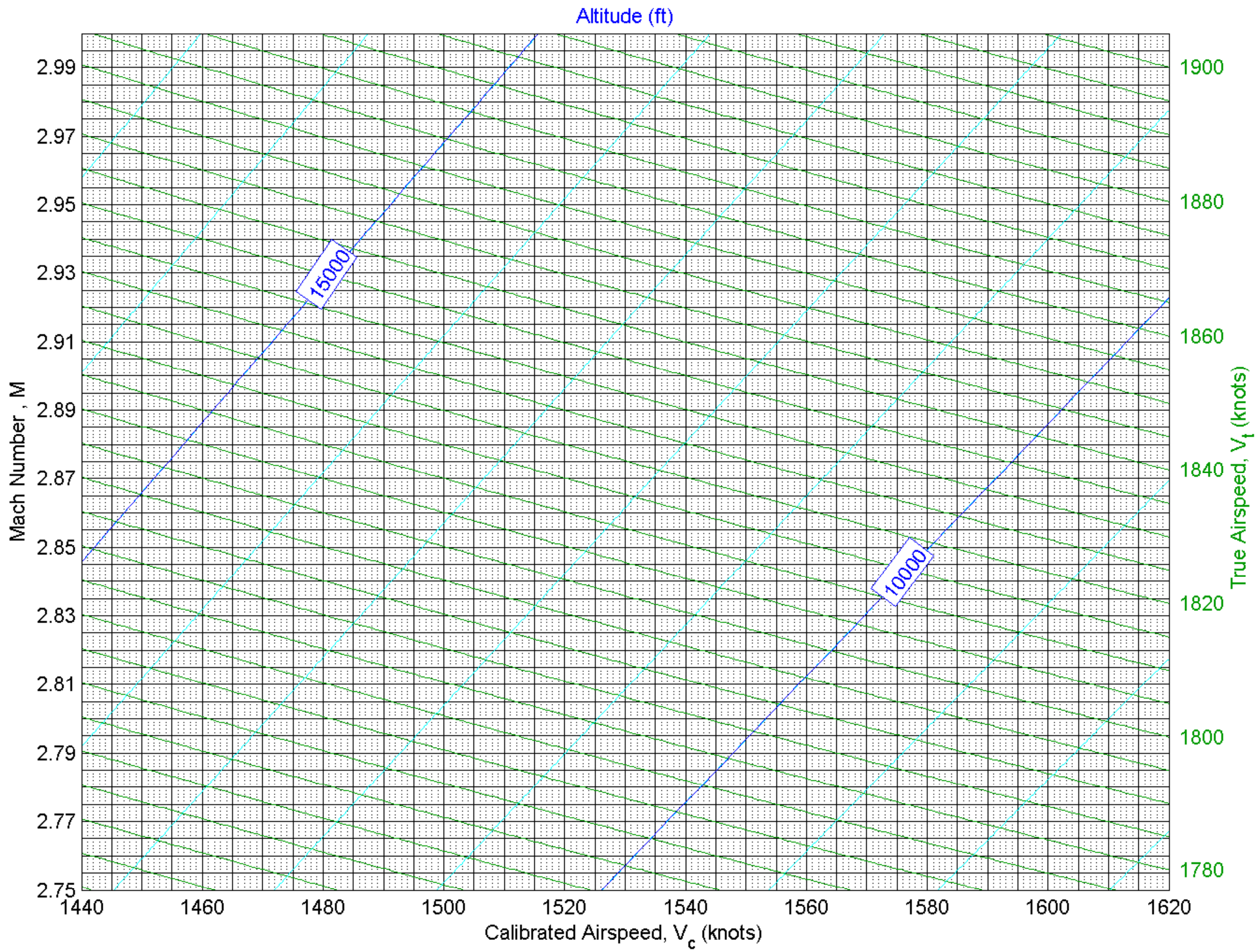
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
1080
1100
1120
1140
1160
1180
1200
1220
1240
1260
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1800
1780
1760
1740
1720
1700


Altitude (ft)
20000
15000
Mach Number , M
2.99
2.97
2.95
2.93
2.91
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
1260
1280
1300
1320
1340
1360
1380
1400
1420
1440
Calibrated Airspeed, V_c (knots)
True Airspeed, V_t (knots)
1840
1820
1800
1780
1760
1740


Altitude (ft)
15000
10000
2.99
2.97
2.95
2.93
2.91
2.89
2.87
2.85
2.83
2.81
2.79
2.77
2.75
Mach Number , M
1440
1460
1480
1500
1520
1540
1560
1580
1600
1620
Calibrated Airspeed, V_c (knots)
1900
1880
1860
1840
1820
1800
1780
True Airspeed, V_t (knots)

APPENDIX G – TABLES OF PRESSURE ALTITUDE, CALIBRATED AIRSPEED, AND MACH NUMBER FOR SUBSONIC MACH NUMBERS

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers

	Mach Number Pressure Altitude (1,000 feet)																
KCAS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
50	0.07559	0.07697	0.07839	0.07984	0.08133	0.08285	0.08442	0.08603	0.08768	0.08938	0.09112	0.09291	0.09474	0.09663	0.09857	0.10056	0.10261
55	0.08315	0.08467	0.08622	0.08782	0.08946	0.09114	0.09286	0.09463	0.09645	0.09831	0.10023	0.10219	0.10421	0.10628	0.10842	0.11061	0.11286
60	0.09071	0.09236	0.09406	0.09580	0.09759	0.09942	0.10130	0.10323	0.10521	0.10724	0.10933	0.11147	0.11367	0.11594	0.11826	0.12065	0.12310
65	0.09826	0.10006	0.10190	0.10378	0.10572	0.10770	0.10974	0.11182	0.11397	0.11617	0.11843	0.12075	0.12313	0.12558	0.12810	0.13068	0.13334
70	0.10582	0.10775	0.10973	0.11176	0.11385	0.11598	0.11817	0.12042	0.12273	0.12510	0.12753	0.13003	0.13259	0.13523	0.13793	0.14072	0.14358
75	0.11338	0.11545	0.11757	0.11974	0.12197	0.12426	0.12661	0.12901	0.13148	0.13402	0.13662	0.13930	0.14205	0.14487	0.14776	0.15074	0.15381
80	0.12094	0.12315	0.12541	0.12772	0.13010	0.13254	0.13504	0.13761	0.14024	0.14294	0.14572	0.14857	0.15150	0.15450	0.15759	0.16077	0.16403
85	0.12850	0.13084	0.13324	0.13570	0.13823	0.14082	0.14347	0.14620	0.14899	0.15186	0.15481	0.15784	0.16094	0.16413	0.16741	0.17078	0.17425
90	0.13606	0.13854	0.14108	0.14368	0.14635	0.14909	0.15190	0.15478	0.15774	0.16078	0.16390	0.16710	0.17039	0.17376	0.17723	0.18080	0.18446
95	0.14362	0.14623	0.14891	0.15166	0.15448	0.15737	0.16033	0.16337	0.16649	0.16969	0.17298	0.17636	0.17983	0.18339	0.18704	0.19080	0.19466
100	0.15118	0.15393	0.15675	0.15964	0.16260	0.16564	0.16876	0.17196	0.17524	0.17861	0.18206	0.18561	0.18926	0.19300	0.19685	0.20080	0.20486
105	0.15874	0.16162	0.16458	0.16761	0.17072	0.17391	0.17718	0.18054	0.18398	0.18752	0.19114	0.19487	0.19869	0.20262	0.20665	0.21079	0.21505
110	0.16629	0.16932	0.17241	0.17559	0.17884	0.18218	0.18561	0.18912	0.19272	0.19642	0.20022	0.20411	0.20812	0.21223	0.21645	0.22078	0.22524
115	0.17385	0.17701	0.18024	0.18356	0.18696	0.19045	0.19403	0.19770	0.20146	0.20532	0.20929	0.21336	0.21754	0.22183	0.22623	0.23076	0.23541
120	0.18141	0.18470	0.18808	0.19154	0.19508	0.19872	0.20245	0.20627	0.21020	0.21422	0.21836	0.22260	0.22695	0.23142	0.23602	0.24073	0.24558
125	0.18897	0.19240	0.19591	0.19951	0.20320	0.20698	0.21086	0.21484	0.21893	0.22312	0.22742	0.23183	0.23636	0.24102	0.24579	0.25070	0.25574
130	0.19653	0.20009	0.20374	0.20748	0.21131	0.21525	0.21928	0.22341	0.22766	0.23201	0.23648	0.24106	0.24577	0.25060	0.25556	0.26066	0.26589
135	0.20409	0.20778	0.21157	0.21545	0.21943	0.22351	0.22769	0.23198	0.23638	0.24090	0.24553	0.25029	0.25517	0.26018	0.26532	0.27061	0.27603
140	0.21165	0.21548	0.21940	0.22342	0.22754	0.23177	0.23610	0.24055	0.24511	0.24978	0.25458	0.25951	0.26456	0.26975	0.27508	0.28055	0.28617
145	0.21921	0.22317	0.22723	0.23139	0.23565	0.24003	0.24451	0.24911	0.25383	0.25866	0.26363	0.26872	0.27395	0.27931	0.28482	0.29048	0.29629
150	0.22676	0.23086	0.23506	0.23936	0.24376	0.24828	0.25292	0.25767	0.26254	0.26754	0.27267	0.27793	0.28333	0.28887	0.29456	0.30040	0.30640
155	0.23432	0.23855	0.24288	0.24732	0.25187	0.25654	0.26132	0.26622	0.27125	0.27641	0.28170	0.28713	0.29270	0.29842	0.30429	0.31032	0.31650
160	0.24188	0.24624	0.25071	0.25529	0.25998	0.26479	0.26972	0.27478	0.27996	0.28528	0.29073	0.29633	0.30207	0.30797	0.31401	0.32022	0.32660
165	0.24944	0.25393	0.25854	0.26325	0.26809	0.27304	0.27812	0.28333	0.28867	0.29414	0.29976	0.30552	0.31143	0.31750	0.32373	0.33012	0.33668
170	0.25700	0.26162	0.26636	0.27122	0.27619	0.28129	0.28651	0.29187	0.29737	0.30300	0.30878	0.31471	0.32079	0.32703	0.33343	0.34000	0.34675

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	Mach Number Pressure Altitude (1,000 feet)																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
175	0.26456	0.26931	0.27419	0.27918	0.28429	0.28953	0.29491	0.30042	0.30606	0.31185	0.31779	0.32389	0.33014	0.33655	0.34313	0.34988	0.35681
180	0.27212	0.27700	0.28201	0.28714	0.29239	0.29778	0.30330	0.30896	0.31476	0.32070	0.32680	0.33306	0.33948	0.34606	0.35281	0.35975	0.36686
185	0.27968	0.28469	0.28983	0.29510	0.30049	0.30602	0.31168	0.31749	0.32344	0.32955	0.33581	0.34222	0.34881	0.35556	0.36249	0.36960	0.37690
190	0.28724	0.29238	0.29765	0.30305	0.30859	0.31426	0.32007	0.32602	0.33213	0.33839	0.34480	0.35138	0.35813	0.36506	0.37216	0.37944	0.38692
195	0.29479	0.30007	0.30547	0.31101	0.31668	0.32249	0.32845	0.33455	0.34081	0.34722	0.35379	0.36054	0.36745	0.37454	0.38182	0.38928	0.39693
200	0.30235	0.30776	0.31329	0.31897	0.32478	0.33073	0.33683	0.34308	0.34948	0.35605	0.36278	0.36968	0.37676	0.38402	0.39146	0.39910	0.40694
205	0.30991	0.31545	0.32111	0.32692	0.33287	0.33896	0.34520	0.35160	0.35815	0.36487	0.37176	0.37882	0.38606	0.39349	0.40110	0.40891	0.41692
210	0.31747	0.32313	0.32893	0.33487	0.34095	0.34719	0.35357	0.36011	0.36682	0.37369	0.38073	0.38795	0.39535	0.40294	0.41073	0.41871	0.42690
215	0.32503	0.33082	0.33675	0.34282	0.34904	0.35541	0.36194	0.36863	0.37548	0.38250	0.38970	0.39708	0.40464	0.41239	0.42035	0.42850	0.43686
220	0.33259	0.33851	0.34457	0.35077	0.35713	0.36364	0.37030	0.37714	0.38413	0.39131	0.39866	0.40619	0.41392	0.42183	0.42995	0.43828	0.44681
225	0.34015	0.34619	0.35238	0.35872	0.36521	0.37186	0.37866	0.38564	0.39279	0.40011	0.40761	0.41530	0.42318	0.43126	0.43955	0.44804	0.45675
230	0.34771	0.35388	0.36020	0.36666	0.37329	0.38007	0.38702	0.39414	0.40143	0.40890	0.41656	0.42440	0.43244	0.44068	0.44913	0.45779	0.46667
235	0.35526	0.36156	0.36801	0.37461	0.38137	0.38829	0.39538	0.40264	0.41007	0.41769	0.42550	0.43350	0.44169	0.45009	0.45870	0.46753	0.47658
240	0.36282	0.36925	0.37582	0.38255	0.38944	0.39650	0.40373	0.41113	0.41871	0.42647	0.43443	0.44258	0.45093	0.45949	0.46827	0.47726	0.48647
245	0.37038	0.37693	0.38363	0.39049	0.39752	0.40471	0.41207	0.41962	0.42734	0.43525	0.44336	0.45166	0.46017	0.46888	0.47782	0.48697	0.49636
250	0.37794	0.38461	0.39144	0.39843	0.40559	0.41291	0.42042	0.42810	0.43596	0.44402	0.45228	0.46073	0.46939	0.47826	0.48736	0.49667	0.50622
255	0.38550	0.39230	0.39925	0.40637	0.41366	0.42112	0.42876	0.43658	0.44458	0.45279	0.46119	0.46979	0.47860	0.48763	0.49688	0.50636	0.51608
260	0.39306	0.39998	0.40706	0.41431	0.42172	0.42932	0.43709	0.44505	0.45320	0.46154	0.47009	0.47884	0.48781	0.49699	0.50640	0.51604	0.52591
265	0.40062	0.40766	0.41487	0.42224	0.42979	0.43751	0.44542	0.45352	0.46181	0.47030	0.47899	0.48789	0.49700	0.50634	0.51590	0.52570	0.53574
270	0.40818	0.41534	0.42267	0.43017	0.43785	0.44571	0.45375	0.46198	0.47041	0.47904	0.48788	0.49692	0.50619	0.51568	0.52540	0.53535	0.54555
275	0.41574	0.42302	0.43048	0.43810	0.44591	0.45390	0.46207	0.47044	0.47901	0.48778	0.49676	0.50595	0.51537	0.52500	0.53488	0.54499	0.55534
280	0.42329	0.43070	0.43828	0.44603	0.45397	0.46209	0.47039	0.47890	0.48760	0.49651	0.50563	0.51497	0.52453	0.53432	0.54434	0.55461	0.56512
285	0.43085	0.43838	0.44608	0.45396	0.46202	0.47027	0.47871	0.48735	0.49619	0.50524	0.51450	0.52398	0.53369	0.54362	0.55380	0.56422	0.57489
290	0.43841	0.44606	0.45388	0.46189	0.47007	0.47845	0.48702	0.49579	0.50477	0.51396	0.52336	0.53298	0.54283	0.55292	0.56324	0.57381	0.58463
295	0.44597	0.45374	0.46168	0.46981	0.47812	0.48663	0.49533	0.50423	0.51334	0.52267	0.53221	0.54197	0.55197	0.56220	0.57267	0.58339	0.59437
300	0.45353	0.46142	0.46948	0.47773	0.48617	0.49480	0.50363	0.51267	0.52191	0.53137	0.54105	0.55096	0.56110	0.57147	0.58209	0.59296	0.60409
305	0.46109	0.46909	0.47728	0.48565	0.49421	0.50297	0.51193	0.52110	0.53048	0.54007	0.54989	0.55993	0.57021	0.58073	0.59150	0.60251	0.61379
310	0.46865	0.47677	0.48507	0.49357	0.50225	0.51114	0.52023	0.52952	0.53903	0.54876	0.55871	0.56890	0.57932	0.58998	0.60089	0.61205	0.62348

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

	Mach Number Pressure Altitude (1,000 feet)																
KCAS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
315	0.47621	0.48444	0.49287	0.50148	0.51029	0.51930	0.52852	0.53794	0.54758	0.55745	0.56753	0.57785	0.58841	0.59922	0.61027	0.62158	0.63315
320	0.48376	0.49212	0.50066	0.50940	0.51833	0.52746	0.53680	0.54636	0.55613	0.56612	0.57635	0.58680	0.59750	0.60844	0.61964	0.63109	0.64281
325	0.49132	0.49979	0.50846	0.51731	0.52636	0.53562	0.54509	0.55477	0.56467	0.57479	0.58515	0.59574	0.60657	0.61766	0.62899	0.64059	0.65245
330	0.49888	0.50747	0.51625	0.52522	0.53439	0.54377	0.55336	0.56317	0.57320	0.58346	0.59394	0.60467	0.61564	0.62686	0.63833	0.65007	0.66208
335	0.50644	0.51514	0.52404	0.53313	0.54242	0.55192	0.56164	0.57157	0.58173	0.59211	0.60273	0.61359	0.62469	0.63605	0.64766	0.65954	0.67168
340	0.51400	0.52281	0.53182	0.54103	0.55045	0.56007	0.56991	0.57996	0.59025	0.60076	0.61151	0.62250	0.63374	0.64523	0.65698	0.66899	0.68128
345	0.52156	0.53049	0.53961	0.54894	0.55847	0.56821	0.57817	0.58835	0.59876	0.60940	0.62028	0.63140	0.64277	0.65439	0.66628	0.67843	0.69086
350	0.52912	0.53816	0.54740	0.55684	0.56649	0.57635	0.58643	0.59674	0.60727	0.61803	0.62904	0.64029	0.65179	0.66355	0.67557	0.68786	0.70042
355	0.53668	0.54583	0.55518	0.56474	0.57451	0.58449	0.59469	0.60511	0.61577	0.62666	0.63779	0.64917	0.66080	0.67269	0.68484	0.69727	0.70997
360	0.54424	0.55350	0.56297	0.57264	0.58252	0.59262	0.60294	0.61349	0.62427	0.63528	0.64654	0.65804	0.66980	0.68182	0.69411	0.70666	0.71950
365	0.55179	0.56117	0.57075	0.58053	0.59053	0.60075	0.61119	0.62185	0.63275	0.64389	0.65528	0.66691	0.67879	0.69094	0.70336	0.71605	0.72901
370	0.55935	0.56884	0.57853	0.58843	0.59854	0.60887	0.61943	0.63022	0.64124	0.65250	0.66400	0.67576	0.68777	0.70005	0.71259	0.72541	0.73851
375	0.56691	0.57651	0.58631	0.59632	0.60655	0.61699	0.62767	0.63857	0.64971	0.66109	0.67272	0.68460	0.69674	0.70915	0.72182	0.73476	0.74799
380	0.57447	0.58417	0.59408	0.60421	0.61455	0.62511	0.63590	0.64692	0.65818	0.66968	0.68143	0.69344	0.70570	0.71823	0.73103	0.74410	0.75746
385	0.58203	0.59184	0.60186	0.61210	0.62255	0.63322	0.64413	0.65527	0.66665	0.67827	0.69014	0.70226	0.71465	0.72730	0.74022	0.75343	0.76691
390	0.58959	0.59951	0.60964	0.61998	0.63055	0.64133	0.65235	0.66361	0.67510	0.68684	0.69883	0.71108	0.72359	0.73636	0.74941	0.76273	0.77635
395	0.59715	0.60717	0.61741	0.62786	0.63854	0.64944	0.66057	0.67194	0.68355	0.69541	0.70752	0.71988	0.73251	0.74541	0.75858	0.77203	0.78576
400	0.60471	0.61484	0.62518	0.63575	0.64653	0.65754	0.66879	0.68027	0.69200	0.70397	0.71619	0.72868	0.74143	0.75444	0.76774	0.78131	0.79517
405	0.61226	0.62250	0.63295	0.64362	0.65452	0.66564	0.67700	0.68859	0.70043	0.71252	0.72486	0.73746	0.75033	0.76347	0.77688	0.79057	0.80456
410	0.61982	0.63017	0.64072	0.65150	0.66250	0.67374	0.68520	0.69691	0.70886	0.72107	0.73352	0.74624	0.75923	0.77248	0.78601	0.79983	0.81393
415	0.62738	0.63783	0.64849	0.65938	0.67049	0.68183	0.69341	0.70522	0.71729	0.72960	0.74218	0.75501	0.76811	0.78148	0.79513	0.80906	0.82328
420	0.63494	0.64549	0.65626	0.66725	0.67847	0.68992	0.70160	0.71353	0.72571	0.73813	0.75082	0.76377	0.77698	0.79047	0.80423	0.81828	0.83262
425	0.64250	0.65315	0.66402	0.67512	0.68644	0.69800	0.70979	0.72183	0.73412	0.74666	0.75945	0.77251	0.78584	0.79944	0.81333	0.82749	0.84195
430	0.65006	0.66081	0.67179	0.68299	0.69442	0.70608	0.71798	0.73013	0.74252	0.75517	0.76808	0.78125	0.79469	0.80841	0.82240	0.83668	0.85126
435	0.65762	0.66847	0.67955	0.69085	0.70239	0.71415	0.72616	0.73842	0.75092	0.76368	0.77670	0.78998	0.80353	0.81736	0.83147	0.84586	0.86055
440	0.66518	0.67613	0.68731	0.69872	0.71035	0.72223	0.73434	0.74670	0.75931	0.77218	0.78531	0.79870	0.81236	0.82630	0.84052	0.85503	0.86983
445	0.67274	0.68379	0.69507	0.70658	0.71832	0.73030	0.74251	0.75498	0.76770	0.78067	0.79391	0.80741	0.82118	0.83523	0.84956	0.86418	0.87909
450	0.68029	0.69145	0.70283	0.71444	0.72628	0.73836	0.75068	0.76325	0.77608	0.78916	0.80250	0.81611	0.82999	0.84415	0.85859	0.87331	0.88833

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	**Mach Number Pressure Altitude (1,000 feet)**																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
455	0.68785	0.69911	0.71059	0.72230	0.73424	0.74642	0.75885	0.77152	0.78445	0.79763	0.81108	0.82480	0.83878	0.85305	0.86760	0.88244	0.89756
460	0.69541	0.70676	0.71834	0.73015	0.74219	0.75448	0.76701	0.77978	0.79281	0.80610	0.81966	0.83348	0.84757	0.86194	0.87660	0.89154	0.90678
465	0.70297	0.71442	0.72610	0.73800	0.75015	0.76253	0.77516	0.78804	0.80117	0.81457	0.82822	0.84215	0.85635	0.87083	0.88559	0.90064	0.91598
470	0.71053	0.72208	0.73385	0.74585	0.75810	0.77058	0.78331	0.79629	0.80953	0.82302	0.83678	0.85081	0.86511	0.87969	0.89456	0.90972	0.92516
475	0.71809	0.72973	0.74160	0.75370	0.76604	0.77863	0.79146	0.80454	0.81787	0.83147	0.84533	0.85946	0.87387	0.88855	0.90352	0.91878	0.93433
480	0.72565	0.73738	0.74935	0.76155	0.77399	0.78667	0.79960	0.81278	0.82621	0.83991	0.85387	0.86810	0.88261	0.89740	0.91247	0.92783	0.94349
485	0.73321	0.74504	0.75710	0.76939	0.78193	0.79471	0.80773	0.82101	0.83455	0.84834	0.86240	0.87674	0.89135	0.90623	0.92141	0.93687	0.95263
490	0.74076	0.75269	0.76485	0.77724	0.78987	0.80274	0.81586	0.82924	0.84287	0.85677	0.87093	0.88536	0.90007	0.91506	0.93033	0.94590	0.96175
495	0.74832	0.76034	0.77259	0.78508	0.79780	0.81077	0.82399	0.83746	0.85119	0.86519	0.87944	0.89398	0.90878	0.92387	0.93924	0.95491	0.97086
500	0.75588	0.76799	0.78034	0.79291	0.80573	0.81880	0.83211	0.84568	0.85951	0.87360	0.88795	0.90258	0.91749	0.93267	0.94814	0.96390	0.97996
505	0.76344	0.77564	0.78808	0.80075	0.81366	0.82682	0.84023	0.85389	0.86782	0.88200	0.89645	0.91118	0.92618	0.94146	0.95703	0.97289	0.98904
510	0.77100	0.78329	0.79582	0.80858	0.82159	0.83484	0.84834	0.86210	0.87612	0.89040	0.90494	0.91976	0.93486	0.95024	0.96590	0.98186	0.99810
515	0.77856	0.79094	0.80356	0.81641	0.82951	0.84286	0.85645	0.87030	0.88441	0.89879	0.91343	0.92834	0.94353	0.95901	0.97476	0.99081	
520	0.78612	0.79859	0.81130	0.82424	0.83743	0.85087	0.86456	0.87850	0.89270	0.90717	0.92190	0.93691	0.95219	0.96776	0.98361	0.99976	
525	0.79368	0.80624	0.81904	0.83207	0.84535	0.85888	0.87266	0.88669	0.90098	0.91554	0.93037	0.94547	0.96085	0.97651	0.99245		
530	0.80124	0.81389	0.82677	0.83990	0.85326	0.86688	0.88075	0.89487	0.90926	0.92391	0.93883	0.95402	0.96949	0.98524			
535	0.80879	0.82153	0.83451	0.84772	0.86118	0.87488	0.88884	0.90305	0.91753	0.93227	0.94728	0.96256	0.97812	0.99396			
540	0.81635	0.82918	0.84224	0.85554	0.86909	0.88288	0.89693	0.91123	0.92579	0.94062	0.95572	0.97109	0.98674				
545	0.82391	0.83682	0.84997	0.86336	0.87699	0.89087	0.90501	0.91940	0.93405	0.94897	0.96416	0.97962	0.99535				
550	0.83147	0.84447	0.85770	0.87117	0.88489	0.89886	0.91308	0.92756	0.94230	0.95731	0.97258	0.98813					
555	0.83903	0.85211	0.86543	0.87899	0.89279	0.90685	0.92116	0.93572	0.95055	0.96564	0.98100	0.99664					
560	0.84659	0.85975	0.87316	0.88680	0.90069	0.91483	0.92922	0.94388	0.95879	0.97397	0.98941						
565	0.85415	0.8674	0.88088	0.89461	0.90859	0.92281	0.93729	0.95202	0.96702	0.98228	0.99782						
570	0.86171	0.87504	0.88861	0.90242	0.91648	0.93079	0.94535	0.96017	0.97525	0.9906							
575	0.86926	0.88268	0.89633	0.91023	0.92437	0.93876	0.9534	0.96831	0.98347	0.9989							
580	0.87682	0.89032	0.90405	0.91803	0.93225	0.94673	0.96145	0.97644	0.99169								
585	0.88438	0.89796	0.91177	0.92583	0.94014	0.95469	0.9695	0.98457	0.9999								
590	0.89194	0.9056	0.91949	0.93363	0.94802	0.96265	0.97754	0.99269									

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	Mach Number Pressure Altitude (1,000 feet)																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
595	0.89950	0.91324	0.92721	0.94143	0.95589	0.97061	0.98558										
600	0.90706	0.92087	0.93493	0.94922	0.96377	0.97856	0.99361										
605	0.91462	0.92851	0.94264	0.95702	0.97164	0.98651											
610	0.92218	0.93615	0.95036	0.96481	0.97951	0.99446											
615	0.92974	0.94378	0.95807	0.9726	0.98738												
620	0.93729	0.95142	0.96578	0.98039	0.99524												
625	0.94485	0.95905	0.97349	0.98817													
630	0.95241	0.96669	0.9812	0.99596													
635	0.95997	0.97432	0.98891	1.00374													
640	0.96753	0.98195	0.99661														
645	0.97509	0.98958															
650	0.98265	0.99721															
655	0.99021																
660	0.99776																
661.48	1.00000																

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

	Mach Number Pressure Altitude (1,000 feet)														
KCAS	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
50	0.10472	0.10689	0.10912	0.11141	0.11377	0.11620	0.11870	0.12128	0.12393	0.12667	0.12949	0.13239	0.13539	0.13848	0.14166
55	0.11518	0.11756	0.12001	0.12253	0.12512	0.12780	0.13055	0.13338	0.13629	0.13930	0.14239	0.14559	0.14888	0.15227	0.15577
60	0.12563	0.12823	0.13090	0.13364	0.13647	0.13938	0.14238	0.14546	0.14864	0.15192	0.15529	0.15877	0.16235	0.16605	0.16986
65	0.13608	0.13889	0.14178	0.14475	0.14781	0.15096	0.15420	0.15754	0.16098	0.16452	0.16817	0.17194	0.17581	0.17981	0.18394
70	0.14652	0.14954	0.15265	0.15585	0.15914	0.16253	0.16602	0.16961	0.17331	0.17712	0.18104	0.18509	0.18926	0.19356	0.19799
75	0.15695	0.16019	0.16352	0.16694	0.17047	0.17409	0.17782	0.18167	0.18562	0.18970	0.19390	0.19823	0.20269	0.20728	0.21202
80	0.16738	0.17083	0.17438	0.17803	0.18178	0.18564	0.18962	0.19371	0.19793	0.20227	0.20674	0.21135	0.21609	0.22099	0.22604
85	0.17781	0.18147	0.18523	0.18910	0.19308	0.19718	0.20140	0.20574	0.21021	0.21482	0.21956	0.22445	0.22948	0.23467	0.24002
90	0.18822	0.19209	0.19607	0.20017	0.20438	0.20871	0.21317	0.21776	0.22249	0.22735	0.23237	0.23753	0.24285	0.24834	0.25399
95	0.19863	0.20271	0.20691	0.21122	0.21566	0.22023	0.22493	0.22977	0.23475	0.23987	0.24515	0.25059	0.25620	0.26197	0.26793
100	0.20903	0.21332	0.21773	0.22227	0.22694	0.23174	0.23667	0.24176	0.24699	0.25238	0.25792	0.26364	0.26952	0.27559	0.28184
105	0.21943	0.22393	0.22855	0.23331	0.23820	0.24323	0.24840	0.25373	0.25921	0.26486	0.27067	0.27666	0.28282	0.28918	0.29572
110	0.22981	0.23452	0.23936	0.24433	0.24945	0.25471	0.26012	0.26569	0.27142	0.27732	0.28340	0.28965	0.29610	0.30274	0.30958
115	0.24019	0.24510	0.25015	0.25534	0.26068	0.26617	0.27182	0.27763	0.28361	0.28977	0.29610	0.30263	0.30935	0.31627	0.32340
120	0.25056	0.25568	0.26094	0.26634	0.27190	0.27762	0.28350	0.28956	0.29578	0.30219	0.30879	0.31558	0.32257	0.32977	0.33719
125	0.26092	0.26624	0.27171	0.27733	0.28311	0.28906	0.29517	0.30146	0.30793	0.31459	0.32144	0.32850	0.33576	0.34325	0.35095
130	0.27127	0.27679	0.28247	0.28831	0.29431	0.30048	0.30682	0.31335	0.32006	0.32697	0.33408	0.34140	0.34893	0.35669	0.36468
135	0.28161	0.28733	0.29322	0.29927	0.30549	0.31188	0.31846	0.32522	0.33217	0.33933	0.34669	0.35427	0.36207	0.37010	0.37837
140	0.29194	0.29786	0.30396	0.31022	0.31665	0.32327	0.33007	0.33707	0.34426	0.35166	0.35927	0.36711	0.37517	0.38348	0.39202
145	0.30225	0.30838	0.31468	0.32115	0.32780	0.33464	0.34167	0.34889	0.35632	0.36397	0.37183	0.37992	0.38825	0.39682	0.40564
150	0.31256	0.31889	0.32539	0.33207	0.33894	0.34599	0.35324	0.36070	0.36837	0.37625	0.38436	0.39271	0.40129	0.41013	0.41922
155	0.32286	0.32938	0.33609	0.34297	0.35005	0.35732	0.36480	0.37249	0.38039	0.38851	0.39687	0.40546	0.41431	0.42340	0.43277
160	0.33314	0.33987	0.34677	0.35386	0.36115	0.36864	0.37634	0.38425	0.39238	0.40074	0.40934	0.41819	0.42728	0.43664	0.44627
165	0.34342	0.35033	0.35744	0.36474	0.37223	0.37994	0.38785	0.39599	0.40435	0.41295	0.42179	0.43088	0.44023	0.44984	0.45974
170	0.35368	0.36079	0.36809	0.37559	0.38330	0.39122	0.39935	0.40771	0.41630	0.42513	0.43421	0.44354	0.45314	0.46301	0.47316
175	0.36393	0.37123	0.37873	0.38643	0.39435	0.40247	0.41082	0.41940	0.42822	0.43728	0.44659	0.45617	0.46601	0.47613	0.48654

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

	Mach Number Pressure Altitude (1,000 feet)														
KCAS	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
180	0.37416	0.38166	0.38935	0.39726	0.40537	0.41371	0.42228	0.43107	0.44011	0.44940	0.45895	0.46876	0.47885	0.48922	0.49988
185	0.38438	0.39207	0.39996	0.40806	0.41638	0.42493	0.43370	0.44272	0.45198	0.46150	0.47128	0.48132	0.49165	0.50227	0.51318
190	0.39459	0.40247	0.41055	0.41885	0.42738	0.43613	0.44511	0.45434	0.46382	0.47356	0.48357	0.49385	0.50442	0.51528	0.52644
195	0.40479	0.41285	0.42113	0.42963	0.43835	0.44730	0.45650	0.46594	0.47564	0.48560	0.49583	0.50634	0.51715	0.52825	0.53965
200	0.41497	0.42322	0.43169	0.44038	0.44930	0.45845	0.46786	0.47751	0.48742	0.49760	0.50806	0.51880	0.52984	0.54117	0.55282
205	0.42514	0.43358	0.44223	0.45111	0.46023	0.46959	0.47919	0.48905	0.49918	0.50958	0.52026	0.53122	0.54249	0.55406	0.56594
210	0.43530	0.44392	0.45276	0.46183	0.47114	0.48070	0.49050	0.50057	0.51091	0.52152	0.53242	0.54361	0.55510	0.56690	0.57902
215	0.44544	0.45424	0.46327	0.47253	0.48203	0.49178	0.50179	0.51207	0.52261	0.53344	0.54455	0.55596	0.56767	0.57970	0.59206
220	0.45557	0.46454	0.47376	0.48321	0.49290	0.50285	0.51306	0.52353	0.53428	0.54532	0.55664	0.56827	0.58021	0.59246	0.60504
225	0.46568	0.47484	0.48423	0.49386	0.50375	0.51389	0.52429	0.53497	0.54592	0.55717	0.56870	0.58055	0.59270	0.60518	0.61799
230	0.47577	0.48511	0.49468	0.50450	0.51458	0.52491	0.53551	0.54638	0.55754	0.56898	0.58073	0.59279	0.60516	0.61785	0.63088
235	0.48586	0.49537	0.50512	0.51512	0.52538	0.53590	0.54669	0.55776	0.56912	0.58077	0.59272	0.60499	0.61757	0.63048	0.64373
240	0.49592	0.50561	0.51554	0.52572	0.53616	0.54687	0.55785	0.56912	0.58067	0.59252	0.60468	0.61715	0.62994	0.64307	0.65653
245	0.50597	0.51583	0.52594	0.53630	0.54693	0.55782	0.56899	0.58045	0.59219	0.60424	0.61660	0.62927	0.64227	0.65561	0.66929
250	0.51601	0.52604	0.53632	0.54686	0.55766	0.56874	0.58010	0.59174	0.60368	0.61593	0.62848	0.64136	0.65457	0.66811	0.68200
255	0.52603	0.53623	0.54668	0.55740	0.56838	0.57964	0.59118	0.60301	0.61514	0.62758	0.64033	0.65341	0.66682	0.68056	0.69466
260	0.53603	0.54640	0.55703	0.56792	0.57908	0.59051	0.60224	0.61426	0.62657	0.63920	0.65215	0.66542	0.67902	0.69297	0.70727
265	0.54602	0.55656	0.56735	0.57841	0.58975	0.60136	0.61327	0.62547	0.63797	0.65079	0.66392	0.67739	0.69119	0.70534	0.71984
270	0.55599	0.56669	0.57766	0.58889	0.60040	0.61219	0.62427	0.63665	0.64934	0.66234	0.67567	0.68932	0.70331	0.71766	0.73235
275	0.56595	0.57681	0.58794	0.59934	0.61102	0.62299	0.63525	0.64781	0.66067	0.67386	0.68737	0.70121	0.71540	0.72993	0.74482
280	0.57589	0.58691	0.59821	0.60977	0.62162	0.63376	0.64619	0.65893	0.67198	0.68534	0.69904	0.71307	0.72744	0.74216	0.75725
285	0.58581	0.59700	0.60845	0.62018	0.63220	0.64451	0.65711	0.67003	0.68325	0.69680	0.71067	0.72488	0.73944	0.75435	0.76962
290	0.59571	0.60706	0.61868	0.63057	0.64276	0.65523	0.66801	0.68109	0.69449	0.70821	0.72227	0.73666	0.75140	0.76649	0.78195
295	0.60560	0.61711	0.62888	0.64094	0.65329	0.66593	0.67887	0.69213	0.70570	0.71959	0.73382	0.74839	0.76331	0.77859	0.79423
300	0.61548	0.62714	0.63907	0.65129	0.66380	0.67660	0.68971	0.70313	0.71687	0.73094	0.74535	0.76009	0.77519	0.79064	0.80646
305	0.62533	0.63715	0.64924	0.66161	0.67428	0.68725	0.70052	0.71411	0.72802	0.74226	0.75683	0.77175	0.78702	0.80265	0.81864
310	0.63517	0.64714	0.65938	0.67192	0.68474	0.69787	0.71131	0.72506	0.73913	0.75354	0.76828	0.78337	0.79881	0.81461	0.83078
315	0.64499	0.65711	0.66951	0.68220	0.69518	0.70847	0.72206	0.73597	0.75021	0.76478	0.77969	0.79495	0.81055	0.82653	0.84287

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	Mach Number Pressure Altitude (1,000 feet)														
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
320	0.65480	0.66706	0.67961	0.69245	0.70559	0.71903	0.73279	0.74686	0.76126	0.77599	0.79107	0.80649	0.82226	0.83840	0.85491
325	0.66458	0.67700	0.68970	0.70269	0.71598	0.72958	0.74349	0.75772	0.77228	0.78717	0.80240	0.81799	0.83393	0.85023	0.86691
330	0.67435	0.68691	0.69976	0.71290	0.72635	0.74010	0.75416	0.76855	0.78326	0.79831	0.81371	0.82945	0.84555	0.86202	0.87885
335	0.68411	0.69681	0.70981	0.72310	0.73669	0.75059	0.76481	0.77935	0.79421	0.80942	0.82497	0.84087	0.85713	0.87376	0.89076
340	0.69384	0.70669	0.71983	0.73327	0.74701	0.76106	0.77542	0.79011	0.80513	0.82049	0.83620	0.85226	0.86867	0.88546	0.90261
345	0.70356	0.71655	0.72983	0.74341	0.75730	0.77150	0.78601	0.80085	0.81602	0.83153	0.84739	0.86360	0.88017	0.89711	0.91442
350	0.71326	0.72639	0.73982	0.75354	0.76757	0.78191	0.79657	0.81156	0.82688	0.84254	0.85855	0.87491	0.89163	0.90872	0.92619
355	0.72295	0.73622	0.74978	0.76364	0.77781	0.79230	0.80711	0.82224	0.83771	0.85351	0.86967	0.88618	0.90305	0.92029	0.93790
360	0.73261	0.74602	0.75972	0.77372	0.78804	0.80266	0.81761	0.83289	0.84850	0.86445	0.88075	0.89741	0.91443	0.93182	0.94958
365	0.74226	0.75580	0.76964	0.78378	0.79823	0.81300	0.82809	0.84351	0.85926	0.87536	0.89180	0.90860	0.92577	0.94330	0.96121
370	0.75189	0.76557	0.77954	0.79382	0.80841	0.82331	0.83854	0.85410	0.86999	0.88623	0.90282	0.91976	0.93706	0.95474	0.97279
375	0.76151	0.77532	0.78942	0.80383	0.81856	0.83360	0.84896	0.86466	0.88069	0.89707	0.91379	0.93088	0.94832	0.96614	0.98433
380	0.77110	0.78504	0.79928	0.81383	0.82868	0.84386	0.85936	0.87519	0.89136	0.90787	0.92474	0.94196	0.95954	0.97749	0.99582
385	0.78068	0.79475	0.80912	0.82380	0.83879	0.85410	0.86973	0.88569	0.90200	0.91865	0.93564	0.95300	0.97072	0.98881	
390	0.79025	0.80444	0.81894	0.83375	0.84887	0.86431	0.88007	0.89617	0.91260	0.92939	0.94652	0.96401	0.98186		
395	0.79979	0.81411	0.82874	0.84367	0.85892	0.87449	0.89039	0.90661	0.92318	0.94009	0.95735	0.97497	0.99296		
400	0.80932	0.82377	0.83852	0.85358	0.86895	0.88465	0.90067	0.91703	0.93373	0.95077	0.96816	0.98591			
405	0.81883	0.83340	0.84828	0.86346	0.87896	0.89478	0.91093	0.92742	0.94424	0.96141	0.97893	0.99680			
410	0.82832	0.84301	0.85801	0.87332	0.88895	0.90489	0.92117	0.93778	0.95472	0.97202	0.98966				
415	0.83780	0.85261	0.86773	0.88316	0.89891	0.91498	0.93138	0.94811	0.96518	0.98260					
420	0.84726	0.86219	0.87743	0.89298	0.90885	0.92504	0.94156	0.95841	0.97560	0.99314					
425	0.85670	0.87175	0.88711	0.90278	0.91876	0.93507	0.95171	0.96868	0.98600						
430	0.86612	0.88129	0.89676	0.91255	0.92866	0.94508	0.96184	0.97893	0.99636						
435	0.87553	0.89081	0.90640	0.92231	0.93853	0.95507	0.97194	0.98915							
440	0.88492	0.90032	0.91602	0.93204	0.94837	0.96503	0.98202	0.99934							
445	0.89429	0.90980	0.92562	0.94175	0.95820	0.97497	0.99207								
450	0.90365	0.91927	0.93520	0.95144	0.96800	0.98488									

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	**Mach Number Pressure Altitude (1,000 feet)**														
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
455	0.91299	0.92872	0.94476	0.96111	0.97778	0.99477									
460	0.92231	0.93815	0.95430	0.97076	0.98754										
465	0.93162	0.94757	0.96382	0.98039	0.99727										
470	0.94091	0.95696	0.97332	0.99000											
475	0.95019	0.96634	0.98281	0.99958											
480	0.95944	0.97570	0.99227												
485	0.96869	0.98505													
490	0.97791	0.99437													
495	0.98712														
500	0.99631														

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

	Mach Number Pressure Altitude (1,000 feet)															
KCAS	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
50	0.14495	0.14834	0.15185	0.15547	0.15920	0.16305	0.16699	0.17102	0.17515	0.17938	0.18370	0.18813	0.19267	0.19731	0.20206	0.20693
55	0.15938	0.16311	0.16696	0.17093	0.17504	0.17926	0.18358	0.18801	0.19254	0.19718	0.20193	0.20679	0.21176	0.21685	0.22207	0.22740
60	0.17380	0.17786	0.18205	0.18637	0.19084	0.19544	0.20015	0.20496	0.20990	0.21494	0.22011	0.22540	0.23081	0.23635	0.24201	0.24781
65	0.18819	0.19258	0.19711	0.20179	0.20662	0.21159	0.21668	0.22188	0.22721	0.23267	0.23825	0.24396	0.24980	0.25578	0.26190	0.26816
70	0.20256	0.20728	0.21215	0.21718	0.22237	0.22771	0.23317	0.23877	0.24449	0.25035	0.25634	0.26247	0.26874	0.27516	0.28172	0.28844
75	0.21691	0.22196	0.22717	0.23254	0.23809	0.24379	0.24963	0.25561	0.26172	0.26798	0.27438	0.28093	0.28762	0.29447	0.30148	0.30864
80	0.23124	0.23661	0.24215	0.24787	0.25377	0.25984	0.26605	0.27241	0.27891	0.28556	0.29236	0.29932	0.30644	0.31372	0.32116	0.32877
85	0.24554	0.25123	0.25711	0.26317	0.26942	0.27585	0.28243	0.28916	0.29605	0.30309	0.31029	0.31766	0.32519	0.33289	0.34076	0.34881
90	0.25982	0.26583	0.27203	0.27843	0.28503	0.29182	0.29877	0.30587	0.31314	0.32057	0.32816	0.33593	0.34387	0.35198	0.36028	0.36876
95	0.27406	0.28039	0.28692	0.29366	0.30061	0.30775	0.31506	0.32253	0.33017	0.33798	0.34597	0.35413	0.36248	0.37100	0.37972	0.38862
100	0.28828	0.29493	0.30178	0.30885	0.31614	0.32363	0.33130	0.33914	0.34715	0.35534	0.36371	0.37226	0.38101	0.38994	0.39907	0.40839
105	0.30247	0.30943	0.31660	0.32400	0.33163	0.33947	0.34749	0.35569	0.36407	0.37263	0.38138	0.39032	0.39946	0.40879	0.41833	0.42807
110	0.31662	0.32389	0.33138	0.33911	0.34707	0.35526	0.36363	0.37219	0.38093	0.38986	0.39898	0.40831	0.41783	0.42756	0.43749	0.44764
115	0.33075	0.33832	0.34613	0.35417	0.36248	0.37100	0.37972	0.38862	0.39772	0.40702	0.41652	0.42621	0.43612	0.44623	0.45656	0.46710
120	0.34483	0.35271	0.36083	0.36920	0.37783	0.38669	0.39575	0.40500	0.41446	0.42411	0.43397	0.44404	0.45432	0.46482	0.47553	0.48647
125	0.35889	0.36707	0.37549	0.38418	0.39313	0.40233	0.41172	0.42132	0.43112	0.44113	0.45135	0.46179	0.47244	0.48331	0.49440	0.50572
130	0.37290	0.38138	0.39011	0.39911	0.40839	0.41791	0.42764	0.43758	0.44772	0.45808	0.46865	0.47945	0.49046	0.50170	0.51316	0.52486
135	0.38688	0.39565	0.40469	0.41400	0.42359	0.43344	0.44350	0.45377	0.46425	0.47495	0.48587	0.49702	0.50839	0.51999	0.53182	0.54389
140	0.40082	0.40988	0.41922	0.42883	0.43874	0.44891	0.45929	0.46989	0.48071	0.49175	0.50301	0.51451	0.52623	0.53818	0.55037	0.56280
145	0.41472	0.42407	0.43370	0.44362	0.45384	0.46432	0.47503	0.48595	0.49710	0.50847	0.52007	0.53190	0.54397	0.55627	0.56882	0.58160
150	0.42858	0.43822	0.44814	0.45836	0.46888	0.47968	0.49069	0.50194	0.51341	0.52511	0.53704	0.54921	0.56161	0.57426	0.58715	0.60028
155	0.44240	0.45232	0.46253	0.47304	0.48386	0.49497	0.50630	0.51786	0.52965	0.54167	0.55393	0.56642	0.57916	0.59214	0.60537	0.61884
160	0.45618	0.46637	0.47687	0.48767	0.49879	0.51020	0.52184	0.53370	0.54581	0.55815	0.57072	0.58354	0.59661	0.60992	0.62347	0.63728
165	0.46991	0.48038	0.49116	0.50225	0.51366	0.52537	0.53731	0.54948	0.56189	0.57454	0.58743	0.60057	0.61395	0.62758	0.64146	0.65560
170	0.48360	0.49435	0.50540	0.51677	0.52847	0.54047	0.55271	0.56518	0.57790	0.59085	0.60405	0.61750	0.63120	0.64514	0.65934	0.67379
175	0.49725	0.50826	0.51959	0.53124	0.54323	0.55552	0.56804	0.58081	0.59382	0.60708	0.62058	0.63434	0.64834	0.66259	0.67710	0.69186

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	**Mach Number Pressure Altitude (1,000 feet)**															
	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
180	0.51085	0.52212	0.53372	0.54565	0.55792	0.57049	0.58331	0.59637	0.60967	0.62322	0.63702	0.65107	0.66538	0.67993	0.69475	0.70981
185	0.52440	0.53594	0.54780	0.56000	0.57255	0.58540	0.59850	0.61185	0.62544	0.63928	0.65337	0.66771	0.68231	0.69716	0.71227	0.72764
190	0.53791	0.54971	0.56183	0.57430	0.58712	0.60025	0.61362	0.62725	0.64112	0.65525	0.66963	0.68426	0.69914	0.71428	0.72968	0.74534
195	0.55137	0.56342	0.57581	0.58854	0.60162	0.61502	0.62868	0.64258	0.65673	0.67113	0.68579	0.70070	0.71587	0.73129	0.74697	0.76291
200	0.56479	0.57709	0.58973	0.60272	0.61607	0.62973	0.64365	0.65782	0.67225	0.68693	0.70186	0.71705	0.73249	0.74819	0.76415	0.78037
205	0.57816	0.59070	0.60359	0.61684	0.63045	0.64438	0.65856	0.67300	0.68769	0.70263	0.71783	0.73329	0.74901	0.76498	0.78121	0.79769
210	0.59147	0.60426	0.61740	0.63090	0.64476	0.65895	0.67339	0.68809	0.70304	0.71825	0.73372	0.74944	0.76542	0.78165	0.79815	0.81490
215	0.60474	0.60426	0.63115	0.64490	0.65901	0.67346	0.68816	0.70311	0.71832	0.73378	0.74951	0.76549	0.78172	0.79822	0.81497	0.83198
220	0.61796	0.61777	0.64485	0.65884	0.67320	0.68789	0.70284	0.71805	0.73351	0.74923	0.76520	0.78143	0.79792	0.81467	0.83168	0.84894
225	0.63113	0.63123	0.65849	0.67272	0.68732	0.70226	0.71746	0.73291	0.74861	0.76458	0.78080	0.79728	0.81402	0.83102	0.84827	0.86577
230	0.64426	0.64463	0.67207	0.68653	0.70138	0.71656	0.73200	0.74769	0.76364	0.77985	0.79631	0.81303	0.83001	0.84725	0.86474	0.88248
235	0.65733	0.65798	0.68560	0.70029	0.71537	0.73079	0.74646	0.76239	0.77858	0.79502	0.81173	0.82869	0.84590	0.86337	0.88110	0.89908
240	0.67035	0.67128	0.69907	0.71399	0.72930	0.74495	0.76085	0.77702	0.79344	0.81011	0.82705	0.84424	0.86169	0.87939	0.89734	0.91555
245	0.68332	0.68452	0.71248	0.72762	0.74316	0.75904	0.77517	0.79156	0.80821	0.82512	0.84228	0.85970	0.87737	0.89529	0.91347	0.93190
250	0.69624	0.69771	0.72583	0.74120	0.75696	0.77306	0.78941	0.80603	0.82290	0.84003	0.85741	0.87505	0.89295	0.91109	0.92949	0.94813
255	0.70911	0.71085	0.73913	0.75471	0.77069	0.78701	0.80358	0.82042	0.83751	0.85486	0.87246	0.89031	0.90842	0.92678	0.94539	0.96425
260	0.72193	0.72393	0.75237	0.76816	0.78435	0.80089	0.81768	0.83473	0.85204	0.86960	0.88741	0.90548	0.92380	0.94237	0.96118	0.98025
265	0.73470	0.73696	0.76555	0.78155	0.79795	0.81470	0.83170	0.84896	0.86648	0.88425	0.90227	0.92055	0.93907	0.95785	0.97687	0.99613
270	0.74742	0.74993	0.77867	0.79488	0.81149	0.82844	0.84565	0.86312	0.88084	0.89882	0.91704	0.93552	0.95425	0.97322	0.99244	
275	0.76008	0.76285	0.79173	0.80814	0.82496	0.84212	0.85953	0.87720	0.89512	0.91330	0.93173	0.95040	0.96932	0.98849		
280	0.77270	0.77572	0.80474	0.82135	0.83836	0.85572	0.87334	0.89120	0.90932	0.92770	0.94632	0.96519	0.98430			
285	0.78526	0.78853	0.81769	0.83449	0.85170	0.86926	0.88707	0.90513	0.92344	0.94201	0.96082	0.97988	0.99918			
290	0.79778	0.80128	0.83058	0.84758	0.86498	0.88273	0.90073	0.91898	0.93748	0.95624	0.97524	0.99448				
295	0.81024	0.81398	0.84342	0.86060	0.87819	0.89613	0.91432	0.93276	0.95145	0.97038	0.98956					
300	0.82265	0.82663	0.85620	0.87356	0.89134	0.90946	0.92783	0.94646	0.96533	0.98444						
305	0.83501	0.83923	0.86892	0.88647	0.90442	0.92273	0.94128	0.96008	0.97913	0.99842						
310	0.84733	0.85177	0.88158	0.89931	0.91744	0.93593	0.95466	0.97364	0.99286							
315	0.85959	0.86426	0.89419	0.91209	0.93040	0.94906	0.96796	0.98711								

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

	Mach Number Pressure Altitude (1,000 feet)															
KCAS	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
320	0.87180	0.87669	0.90674	0.92482	0.94330	0.96213	0.98120									
325	0.88396	0.88907	0.91924	0.93748	0.95613	0.97513	0.99437									
330	0.89607	0.90140	0.93168	0.95009	0.96890	0.98807										
335	0.90814	0.91368	0.94407	0.96264	0.98162											
340	0.92015	0.92591	0.95640	0.97513	0.99427											
345	0.93212	0.93808	0.96868	0.98756												
350	0.94403	0.95020	0.98090	0.99994												
355	0.95590	0.96227	0.99307													
360	0.96772	0.97429														
365	0.97950	0.98626														
370	0.99122	0.99818														

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	Mach Number Pressure Altitude (1,000 feet)											
	48	49	50	51	52	53	54	55	56	57	58	59
50	0.21190	0.21700	0.22221	0.22755	0.23301	0.23860	0.24432	0.25017	0.25616	0.26229	0.26855	0.27497
55	0.23286	0.23844	0.24416	0.25001	0.25599	0.26211	0.26838	0.27479	0.28134	0.28805	0.29491	0.30192
60	0.25375	0.25982	0.26603	0.27238	0.27888	0.28553	0.29234	0.29929	0.30641	0.31368	0.32113	0.32873
65	0.27456	0.28112	0.28782	0.29467	0.30168	0.30885	0.31618	0.32368	0.33135	0.33918	0.34720	0.35539
70	0.29531	0.30233	0.30952	0.31686	0.32438	0.33206	0.33991	0.34794	0.35615	0.36454	0.37311	0.38187
75	0.31597	0.32346	0.33112	0.33896	0.34696	0.35515	0.36352	0.37207	0.38080	0.38973	0.39886	0.40818
80	0.33655	0.34450	0.35263	0.36094	0.36944	0.37812	0.38699	0.39605	0.40531	0.41477	0.42443	0.43430
85	0.35703	0.36544	0.37404	0.38282	0.39179	0.40096	0.41032	0.41989	0.42966	0.43964	0.44983	0.46023
90	0.37743	0.38628	0.39533	0.40458	0.41402	0.42367	0.43352	0.44358	0.45385	0.46433	0.47504	0.48596
95	0.39772	0.40702	0.41652	0.42622	0.43612	0.44624	0.45656	0.46710	0.47786	0.48885	0.50005	0.51148
100	0.41792	0.42765	0.43758	0.44773	0.45809	0.46866	0.47945	0.49047	0.50171	0.51317	0.52487	0.53680
105	0.43801	0.44816	0.45853	0.46911	0.47992	0.49094	0.50219	0.51366	0.52537	0.53731	0.54948	0.56189
110	0.45799	0.46856	0.47935	0.49037	0.50160	0.51307	0.52476	0.53669	0.54885	0.56125	0.57388	0.58676
115	0.47786	0.48885	0.50005	0.51148	0.52315	0.53504	0.54717	0.55953	0.57214	0.58499	0.59808	0.61141
120	0.49762	0.50901	0.52062	0.53246	0.54454	0.55685	0.56941	0.58220	0.59524	0.60852	0.62205	0.63583
125	0.51726	0.52904	0.54105	0.55330	0.56578	0.57851	0.59148	0.60469	0.61815	0.63186	0.64581	0.66002
130	0.53679	0.54895	0.56135	0.57399	0.58687	0.60000	0.61337	0.62699	0.64086	0.65498	0.66935	0.68398
135	0.55619	0.56873	0.58151	0.59454	0.60781	0.62132	0.63509	0.64911	0.66338	0.67790	0.69267	0.70770
140	0.57547	0.58838	0.60154	0.61494	0.62858	0.64248	0.65663	0.67103	0.68569	0.70060	0.71577	0.73119
145	0.59463	0.60790	0.62142	0.63518	0.64920	0.66347	0.67800	0.69277	0.70781	0.72309	0.73864	0.75444
150	0.61366	0.62728	0.64116	0.65528	0.66966	0.68429	0.69918	0.71432	0.72972	0.74537	0.76129	0.77746
155	0.63256	0.64653	0.66075	0.67523	0.68996	0.70494	0.72018	0.73568	0.75143	0.76744	0.78371	0.80024
160	0.65133	0.66564	0.68020	0.69502	0.71009	0.72542	0.74100	0.75684	0.77294	0.78930	0.80591	0.82278
165	0.66998	0.68462	0.69951	0.71466	0.73006	0.74572	0.76164	0.77782	0.79425	0.81094	0.82789	0.84509
170	0.68849	0.70345	0.71867	0.73414	0.74987	0.76585	0.78210	0.79860	0.81536	0.83237	0.84964	0.86717
175	0.70688	0.72215	0.73768	0.75347	0.76951	0.78582	0.80237	0.81919	0.83626	0.85359	0.87117	0.88901
180	0.72513	0.74071	0.75655	0.77264	0.78900	0.80560	0.82247	0.83959	0.85697	0.87460	0.89249	0.91063
185	0.74326	0.75914	0.77527	0.79166	0.80831	0.82522	0.84239	0.85980	0.87748	0.89540	0.91358	0.93201

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Continued)

KCAS	Mach Number Pressure Altitude (1,000 feet)											
	48	49	50	51	52	53	54	55	56	57	58	59
190	0.76125	0.77742	0.79385	0.81053	0.82747	0.84467	0.86212	0.87983	0.89779	0.91600	0.93446	0.95318
195	0.77911	0.79556	0.81227	0.82924	0.84647	0.86394	0.88168	0.89966	0.91790	0.93639	0.95513	0.97411
200	0.79684	0.81357	0.83056	0.84780	0.86530	0.88305	0.90106	0.91932	0.93782	0.95658	0.97558	0.99483
205	0.81444	0.83144	0.84869	0.86621	0.88397	0.90199	0.92026	0.93878	0.95755	0.97657	0.99583	
210	0.83191	0.84917	0.86669	0.88446	0.90249	0.92076	0.93929	0.95807	0.97709	0.99636		
215	0.84924	0.86676	0.88454	0.90256	0.92084	0.93937	0.95815	0.97717	0.99644			
220	0.86645	0.88422	0.90224	0.92052	0.93904	0.95781	0.97683	0.99610				
225	0.88353	0.90154	0.91981	0.93832	0.95709	0.97610	0.99535					
230	0.90048	0.91873	0.93723	0.95598	0.97498	0.99422						
235	0.91731	0.93579	0.95452	0.97349	0.99271							
240	0.93400	0.95271	0.97166	0.99086								
245	0.95058	0.96950	0.98867									
250	0.96703	0.98616										
255	0.98335											
260	0.99955											

Table G1 Pressure Altitude, Calibrated Airspeed, and Mach Number for Subsonic Mach Numbers (Concluded)

KCAS	Mach Number Pressure Altitude (1,000 feet)					
	60	61	62	63	64	65
50	0.28153	0.28824	0.29510	0.30212	0.30930	0.31664
55	0.30910	0.31644	0.32394	0.33161	0.33946	0.34747
60	0.33651	0.34447	0.35260	0.36091	0.36940	0.37808
65	0.36376	0.37231	0.38106	0.38999	0.39912	0.40845
70	0.39082	0.39997	0.40931	0.41886	0.42861	0.43857
75	0.41770	0.42742	0.43735	0.44749	0.45785	0.46842
80	0.44438	0.45467	0.46517	0.47589	0.48683	0.49799
85	0.47085	0.48169	0.49275	0.50403	0.51554	0.52729
90	0.49711	0.50848	0.52008	0.53192	0.54398	0.55629
95	0.52315	0.53504	0.54717	0.55954	0.57214	0.58499
100	0.54896	0.56136	0.57400	0.58688	0.60001	0.61338
105	0.57454	0.58743	0.60057	0.61395	0.62758	0.64146
110	0.59989	0.61326	0.62688	0.64074	0.65486	0.66923
115	0.62500	0.63883	0.65291	0.66725	0.68184	0.69668
120	0.64986	0.66415	0.67868	0.69347	0.70851	0.72382
125	0.67449	0.68920	0.70417	0.71940	0.73488	0.75063
130	0.69886	0.71400	0.72939	0.74504	0.76095	0.77711
135	0.72299	0.73853	0.75434	0.77039	0.78671	0.80328
140	0.74687	0.76281	0.77900	0.79545	0.81216	0.82913
145	0.77050	0.78682	0.80339	0.82023	0.83731	0.85466
150	0.79389	0.81057	0.82751	0.84471	0.86216	0.87987
155	0.81702	0.83406	0.85136	0.86891	0.88671	0.90477
160	0.83991	0.85729	0.87493	0.89282	0.91096	0.92936
165	0.86255	0.88026	0.89823	0.91645	0.93492	0.95364
170	0.88495	0.90298	0.92126	0.93980	0.95858	0.97761
180	0.90710	0.92544	0.94403	0.96287	0.98196	
185	0.92902	0.94766	0.96654	0.98567		
190	0.95069	0.96962	0.98879			
195	0.97213	0.99134				
200	0.99334					

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APPENDIX H - LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition	Units
A	incremental surface area on an element of air in vertical equilibrium	---
a	ambient air temperature lapse rate with geopotential altitude in the troposphere	---
a	local speed of sound	---
a_{SL}	speed of sound at sea level on a standard day	---
AFB	Air Force Base	---
AFFTC	Air Force Flight Test Center	---
AGARD	Advisory Group for Aeronautical Research and Development	---
C	Celsius	degrees
CA	California	---
deg	degree	---
deg C	degree Celsius	degrees
deg R	degree Rankine	degrees
dH	incremental change in geopotential height	---
DoD	Department of Defense	---
dP	incremental change in ambient air pressure	---
DTIC	Defense Technical Information Center	---
dV	incremental volume of an element of air in vertical equilibrium	---
dZ	incremental change in geometric height	---
e	base of natural logarithms, approximately equal to 2.718 281 828	---
EAR	Export Arms Regulation	---
F	Force, Fahrenheit	degrees
ft	international foot or feet, length exactly equal to 0.3048 of a meter	---
g	local acceleration due to gravity	---
g_0	reference value for the acceleration due to gravity, equal to 9.80665 meter per second squared	---
H	geopotential height above mean sea level	---
H_0	geopotential height at mean sea level, equal to zero by definition	---

Abbreviation	**Definition**	**Units**
H_1	geopotential height at the top of the troposphere, at the tropopause, 11,000 meters above mean sea level	---
H_p	pressure altitude	---
Hg	mercury	---
hPa	hectopascals, one hundred pascals and equal to a millibar of pressure	---
ICAO	International Civil Aviation Organization	---
in	inch, length of exactly 0.025 400 of a meter	---
Inc.	Incorporated	---
in Hg	inch of mercury	---
JON	job order number	---
K	kelvin, a unit of temperature, formerly a degree Kelvin	---
K_R	total air temperature probe recovery factor	---
KCAS	knots calibrated airspeed	knots
kg	kilogram, unit of mass in the SI system	---
kmol	symbol for kilomole, an SI unit for mass equal to 1,000 moles	---
lb_f	pound force	---
lb_m	pound mass	---
ln	natural logarithm	---
M	Mach number or molecular weight	---
M_1	freestream Mach number in appendix B	---
M_2	Mach number behind a normal shock in appendix B	---
m	meter	---
mb	millibar, a unit of atmospheric pressure used by the U.S. Weather Bureau	---
N	newton, a unit of force in the SI system equal to one $kg \cdot m/(sec)^2$	---
N/A	not applicable	---
NACA	National Advisory Committee for Aeronautics	---
NASA	National Aeronautics and Space Administration	---
NATO	North Atlantic Treaty Organization	---
n/d	non-dimensional	---

Abbreviation	Definition	Units
NIST	National Institute of Standards and Technology, part of the U.S. Department of Commerce	---
nm	nautical mile	---
NOAA	National Oceanic and Atmospheric Administration, part of the U.S. Department of Commerce	---
NTIS	National Technical Information Service	---
P	ambient air pressure	---
P_a	ambient or static air pressure	---
Pa	pascal, a unit of pressure in the SI system equal to one newton per square meter or one $kg/(m \cdot sec^2)$	---
psia	pounds force per square inch absolute	---
P_{SL}	ambient air pressure at sea level on a standard day	---
P_T	total air pressure	---
P_{T_2}	total air pressure behind a normal shock in appendix B	---
P_0	ambient air pressure at the bottom of the troposphere (sea level) on a standard day, equal to P_{SL}	---
P_1	ambient air pressure at the top of the troposphere (at the tropopause) on a standard day or freestream ambient air pressure ahead of a normal shock in appendix B	---
P_2	static air pressure immediately behind a normal shock in appendix B	---
q	incompressible dynamic pressure	---
q_c	compressible dynamic pressure (also known as differential pressure, q_d), P_T - P_a	---
q_d	differential pressure, P_T - P_a	---
R	Rankine or specific gas constant	---
R^*	universal gas constant	---
r_0	reference radius for the Earth, 6,356.766 kilometers	---
sec	second	---
SI	International System of Units, the metric system	---
T	ambient air temperature	---
T_a	ambient air temperature	---

Abbreviation	**Definition**	**Units**
T_0	ambient air temperature at the bottom of the troposphere (at sea level) on a standard day, 15 degrees Celsius or 288.15K, equal to T_{SL}	---
TIH	technical information handbook	---
T_{SL}	ambient air temperature at sea level on a standard day, 15 degrees Celsius or 288.15 K	---
T_T	total air temperature	---
$T_{T_{ic}}$	instrument-corrected, indicated total air temperature	---
U.S.	United States	---
U.S.C.	United States Code	---
V_c	calibrated airspeed	---
V_e	equivalent airspeed	---
V_{ic}	instrument-corrected, indicated airspeed	---
V_i	indicated airspeed	---
V_I	alternate symbol for V_{ic}	---
V_T	true airspeed	---
Z	geometric height above mean sea level	---
δ	ambient air pressure ratio, P/P_{SL}	---
ΔP	incremental change in pressure	---
ΔPE	change in potential energy	---
ΔZ	incremental change in geometric height	---
ΔV_{ic}	airspeed instrument correction to be added to the indicated airspeed to account for mechanical errors in the instrument (determined in a laboratory test)	---
ΔV_c	airspeed correction to be added to the calibrated airspeed (if negative) or to be subtracted (if positive) to calculate the equivalent airspeed	---
ΔV_{pc}	airspeed correction to be added to the instrument-corrected, indicated airspeed to account for errors in sensing the ambient air pressure (must be determined in flight)	---
θ	ambient air temperature ratio, T/T_{SL}	---
σ	ambient air density ratio, ρ/ρ_{SL}	---

Abbreviation	Definition	Units
γ	ratio of specific heats, assumed for this handbook to be exactly equal to 1.400	---
ρ	ambient air density	---
ρ_{SL}	ambient air density at sea level on a standard day	---
(The following terms are subscripted.)		
$_{i}$	indicated	---
$_{ic}$	instrument-corrected	---
$_{c}$	calibrated (as in V_c) or compressibility (as in ΔV_c)	---
$_{e}$	equivalent	---
$_{SL}$	sea level	---
$_{T}$	true or total	---
$_{0}$	bottom of the troposphere, sea level	---
$_{1}$	top of the troposphere, the tropopause or ahead of a normal shock in appendix B	---
$_{2}$	behind a normal shock in appendix B	---

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